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Nitrogen management studies in irrigated rice

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(Editors)

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Preface

This volume of SARP Research Proceedings compiles the papers on nitrogen (N) related rice research presented during the SARP Applications Workshop held at IRRI in April-May 1994, and also the subsequent results obtained afterwards by various centres participating in the SARP research network.

The simple dynamic model ORYZA_0 was introduced in 1994 to derive optimum N fertilizer application strategies for irrigated rice under specified varietal and environmental conditions. One of the papers presented during the workshop already included the ORYZA_0 recommendations derives with the help of the earliest version of the model. Since then considerable refinement of the model has taken place although the basic approach remained the same. These evolution's can be discerned from the first three papers in this volume which are based on different versions of the model. At an early stage, the model recommendations were tested in the field at IRRI during the dry season 1994 and the results are briefly presented in the fourth paper. Testing at a wide scale is currently under way at various sites in China, India and other countries.

The ORYZA_0 version has now been integrated into a user-friendly shell package, MANAGE-N, which now optimizes grain yield rather than total biomass.

The next four papers describe the effects of N application on root activity, sink - source relationships, recovery of applied N and on tillering pattern which provide more insight in the crop processes and related N management aspects. The paper on optimization of N and LAI for maximum canopy assimilation rate emphasizes the significance of N distribution over leaf canopy. The paper on the procedure for plant sample collection provided a guideline for Common Experiment IV, proposed during the Applications Workshop. The last paper on soil fertility evaluation focuses on the importance of evaluating the soil N supply for optimized N application.

Wageningen
May, 1995

The Editors

Contents

Optimization of nitrogen management for hybrid rice: a simulation approach

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Introduction

Different agroclimatic and soil conditions, and cultural practices cause variations in rice yields. In most parts of South China, irrigation is fully controlled for irrigated rice. Rice yield is mainly a function of climatic conditions and the soil nutrient status. Nitrogen is the most common limiting factor.

The response of rice to fertilizer nitrogen application has been studied intensively over the past decades (Panse & Khanna, 1964; Bouldin, 1986; De Datta & Patrick, 1986; Thiyagarajan et al., 1991). An important conclusion from those studies is that there is enormous variability in the effectiveness of N management strategies across environments. Insufficient or inappropriate fertilizer nitrogen management may account for one-half to two-third of the gap between actual and potential irrigated rice yields. Our understanding of the mechanisms controlling N uptake is still only fragmentary, although there are several N application techniques that are being utilized in rice production at present.

With the help of dynamic models, knowledge about soil and crop processes can be integrated in order to quantify the behaviour of N uptake and N utilization by the crop. Recently, a largely empirical model describing nitrogen uptake and subsequent dry matter production by rice has become available (ten Berge et al., 1994). This model, ORYZA_0, *version* 1.0, is used here as a framework to analyse experimental data obtained from a field experiment on nitrogen management conducted at Jinhua in 1993.

Materials and methods

Experiment

In the late season 1993, a field experiment was conducted in Jinhua county in the south of Zhejiang Province (latitude 27-31°N), China, with cultivar Xieyou 10, a medium-maturing hybrid rice. One seedling (37 day old) was planted per hill with a density of 20 hills m^{-2}. The trial consisted of a randomized block design with four replications and with different nitrogen application levels (0, 150, 180, 210, 240, 270, and 300 kg N ha^{-1}) in two splits;

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Table 1. Overview of timing and rate of fertilizer N application for the field experiment at Jinhua, late season 1993.

Treatment codes	N applied (kg N ha^{-1})		
	0 DAT	7 DAT	Total
T0	0	0	0
T1	90	60	150
T2	108	72	180
T3	126	84	210
T4	144	96	240
T5	162	08	270
T6	180	20	300

60% as basal and 40% seven days after transplanting (Table 1). P_2O_5 (45 kg ha^{-1})and K_2O (60 kg ha^{-1}) fertilizers were applied basally.

For the analysis of growth and nitrogen distribution, nine and later (after the end of tillering) six hills were sampled at seven days intervals. The plants were separated into roots, stems including leaf sheaths, leaves (green and dead leaves) and storage organs, and dried, weighed and analysed for nitrogen. The dynamics of tillering and physiological maturity were also recorded. Daily weather data were collected from a local weather station five kilometres away from the experimental field.

Model and input parameters

The simple dynamic model ORYZA_0 includes N uptake, partitioning of N to the leaf canopy; and the utilization of leaf N in converting daily incident global radiation into dry matter. When combined with a numerical optimization procedure, ORYZA_0 generates a recommendation of the amount and timing of fertilizer-N application needed to achieve maximum biomass or grain yield (ten Berge et al., 1994). Most of the input parameters and functions were directly derived from the Jinhua experimental data, which included soil and crop characteristics. Subsequently, the optimization procedure was used to identify four parameters defining a generalized logistic cumulative N application curve as a function of time.

Results and discussion

Dry matter production and grain yield

Total dry matter production at different stages for all N application levels were higher than zero N but the differences between the treatments that received N were not large. High N

Table 2. Yield and yield components and the dry matter partitioning at harvest for cvar Xieyou 10 at Jinhua, late season 1993. Treatment codes are explained in Table 1.

	T0	T1	T2	T3	T4	T5	T6
Yield and yield components							
max. number of stems (10^6 ha^{-1})	2.89	4.17	4.34	4.52	4.73	5.05	5.10
max. no. of productive stems (10^6 ha^{-1})	2.30	3.25	3.30	3.35	3.42	3.48	3.53
number of spikelets per panicle	86	97	99	103	107	111	113
setting percentage (%)	87.0	85.6	86.3	82.4	77.2	72.3	67.6
grain yield (0% moisture, t ha^{-1})	4.63	7.26	7.74	7.69	7.50	7.26	7.21
Partitioning of dry matter							
leaf mass (t ha^{-1})	1.08	1.84	2.10	2.33	2.51	2.59	2.76
stem mass (t ha^{-1})	2.71	3.53	3.53	3.63	4.02	4.35	4.45
root mass (t ha^{-1})	0.59	0.83	0.85	0.93	0.87	0.85	0.88
panicle mass (t ha^{-1})	5.08	7.95	8.83	8.72	8.47	8.29	8.21
total crop biomass (t ha^{-1})	9.5	14.1	15.3	15.6	15.9	16.1	16.3
Harvest index (HI)	0.49	0.51	0.51	0.50	0.47	0.45	0.44

input levels resulted in a larger number of stems, a greater number of spikelets per panicle,but a lower setting percentage and harvest index (HI). As a result, higher fertilizer-N application did not lead to increased grain yield, but only resulted in increased leaf and stem biomass (Table 2).

Fertilizer-N uptake : the relative N uptake coefficient and limitations

Total N uptake exhibited a positive relation with N application ($Y= 0.542X + 93.61$). The results were in agreement with those reported by De Datta & Patrick (1986) showing that N uptake is linearly related with the amount of N application. If nitrogen is available in the soil, N uptake in early stages is governed by the N relative uptake coefficient (RUR). In the present experiment, an exponential increase in N uptake during the first two weeks after transplanting was observed. The corresponding value of RUR during this stage was found to be 0.149 d^{-1}.

After the exponential stage, N uptake may be limited by the maximum daily nitrogen uptake rate (MAXUP1); the maximum ratio of daily N uptake to daily biomass production (NUPCO); the maximum amount of nitrogen in leaves (ANLVMX), and the maximum overall concentration of N in the total crop biomass as a function of days after transplanting (FNMAXT). Using the complete Jinhua experimental dataset, the following values were derived:

MAXUP1 = 7.9 kg N $ha^{-1}d^{-1}$
NUPCO = 0.030 kg N kg^{-1}
ANLVMX = 100 kg N ha^{-1}
FUNCTION FNMAXT = 0., 0.016, 21., 0.026, 49., 0.021, 70., 0.017, 91., 0.015

Allocation and redistribution of nitrogen

The nitrogen accumulation in the leaves over time was measured in more detail (Figure 1). It rapidly increased for all treatments up to first flowering (42 DAT) and decreased continuously thereafter.

The fraction of N in leaf (FNCLV) was relatively stable (0.47) for all treatments during crop development up to first flowering. From the onset of flowering, most of the crop N is reallocated from leaf and non-leaf vegetative tissues to panicle. Considerable variation in fraction of N in panicles (FNSO) among treatments was observed. A mean value of 0.0159 g g^{-1} was used.

Assessment of the initial leaf nitrogen use coefficient p by calibration

The initial leaf nitrogen use coefficient is one of major input parameters, which represents the overall efficiency by which leaf nitrogen is used to produce dry matter. In the process of

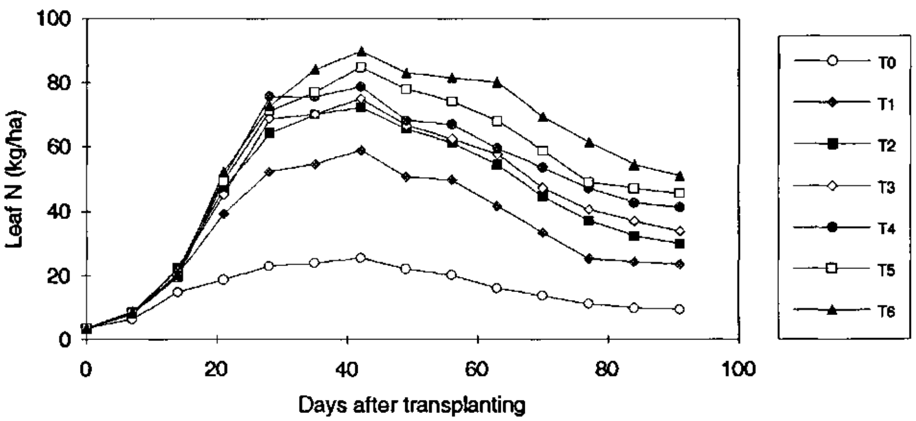

Figure 1. Observed leaf N accumulation as a function of days after transplanting for all treatments, cvar Xieyou10 at Jinhua, 1993. Treatment codes are explained in Table 1.

calibrating the p value, it was found that the simulated crop biomass accumulation after first flowering was remarkably higher than observed in all treatments, when it was calculated with the help of a single p value (of p = 11 g g^{-1} d^{-1}) derived from preflowering growth. We used, therefore, different p values to describe biomass accumulation in the preflowering and postflowering phases respectively (Figure 2). This change in leaf nitrogen use coefficient after first flowering is not understood at the moment and certainly merits further investigation. Such a pattern was not observed earlier in nine other datasets (ten Berge et al., 1994).

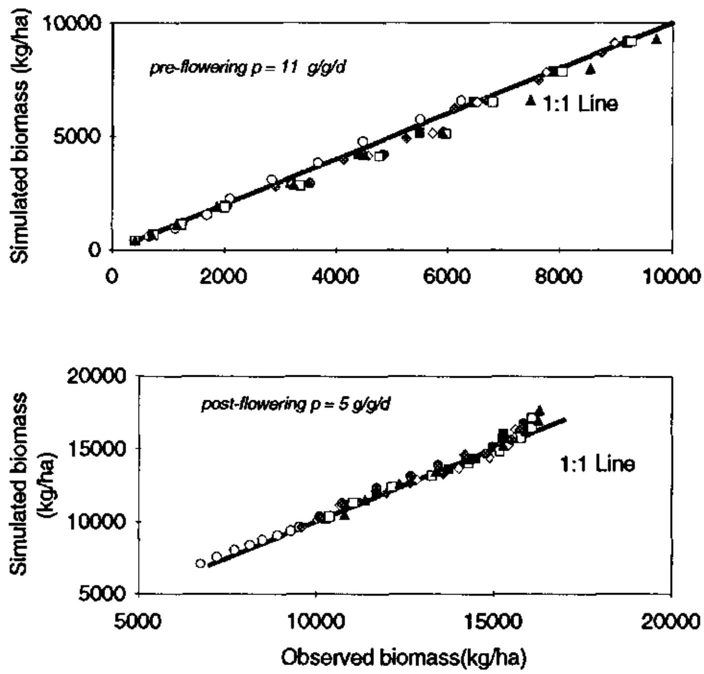

Figure 2. Simulated vs. observed total crop biomass for *cvar* Xieyou 10, Jinhua, late season 1993. The simulated values were derived after calibration of p for pre- and post-flowering phases, separately.

Figure 2 shows that biomass accumulation in all treatments was described accurately with the help of these two p values. These values were therefore used in the optimization phase.

A list of all the input parameters and function derived from the present experiment is given in Table 3. Initial global radiation use coefficient (EPS) and radiation effectivity coefficient (RRC) are constants. The native soil N supply rate (SOLSUP) was derived from the uptake in non-fertilized plots. The table of potential fertilizer-N recovery vs. time, (RECT), was derived from literature and previous experiments. Most of above parameters and functions used with ORYZA_0 are supposed to be varietal and environmental characteristics. The sensitivity of grain production to these factors is subject to further experimental and modelling studies. We used here the first release of ORYZA_0. (Later versions of ORYZA_0 use fixed values of p and EPS, and no longer include RRC. Calibration is performed with the newly introduced factor FSV).

Table 3. Parameters and functions used in ORYZA_0 model (version 1.) Other input parameters are used in later versions. Crop specific data for hybrid rice *cvar* Xieyou 10 as observed at Jinhua, late season 1993.

Crop parameters and functions			unit
CONSTANT	EPS	= 3.5	g MJ^{-1}
CONSTANT	RRC	= 0.035	m^2 d MJ^{-1}
PARAM	FNCLV	= 0.473	g g^{-1}
PARAM	RUR	= 0.149	d^{-1}
PARAM	FNSO	= 0.0159	g g^{-1}
PARAM	NUPCO	= 0.030	g g^{-1}
PARAM	MAXUP1	= 7.94	kg $ha^{-1}d^{-1}$
PARAM	ANLVMX	= 100	kg ha^{-1}
FUNCTION	FNMAXT	= 0., 0.0156, 21., 0.026, 49., 0.021, 70., 0.017, 91., 0.0152	g g^{-1}
Soil parameters and functions			
PARAM	SOLSUP	= 0.980	kg ha^{-1} d^{-1}
FUNCTION	RECT	= 0.,0.2, 25.,0.85, 50.,0.85, 75., 0.0, 91., 0.0	

Recommendation curve for N application

The Price algorithm as documented by Stol et al. (1994) was applied in combination with ORYZA_0 to identify the optimum values of a, b, c, and m, which define a generalized logistic cumulative N application curve. This was repeated for each of nine nitrogen input levels (FERTMX): 0, 50, 100, 150, 180, 210, 240, 270, and 300 kg N ha^{-1}. Each of the input levels had a corresponding optimum combination of a, b, c, and m. The resulting N response curve (Figure 3) shows the highest attainable biomass under each N application level which were very close to observed values.

The eight fertilizer recommendation curves corresponding to the input levels are given in Figure 4. Three preliminary conclusions can be drawn from this figure. (1) At low input levels (e.g. 50 and 100 kg N ha^{-1}), the best strategy is to apply almost all fertilizer prior to

27 DAT (before panicle initiation stage), (2) with higher N input levels, N to be applied after PI increases in proportion to in the total input, but 90-100% of total N should be applied before 40 DAT (first flowering stage), and (3) the same N management strategy can be followed when total N application exceeds one threshold value. These conclusions have great implications to present rice production practice in the study area.

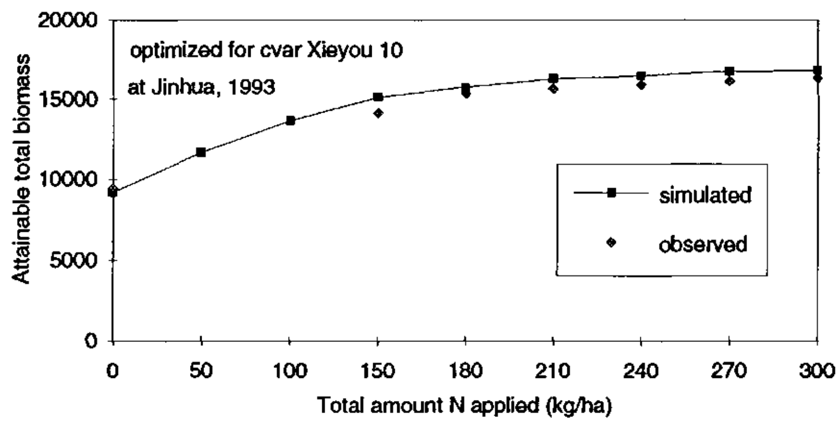

Figure 3. Maximum attainable total crop biomass production simulated for selected N input leaves, for cvar Xieyou 10 at Jinhua, late season 1993.

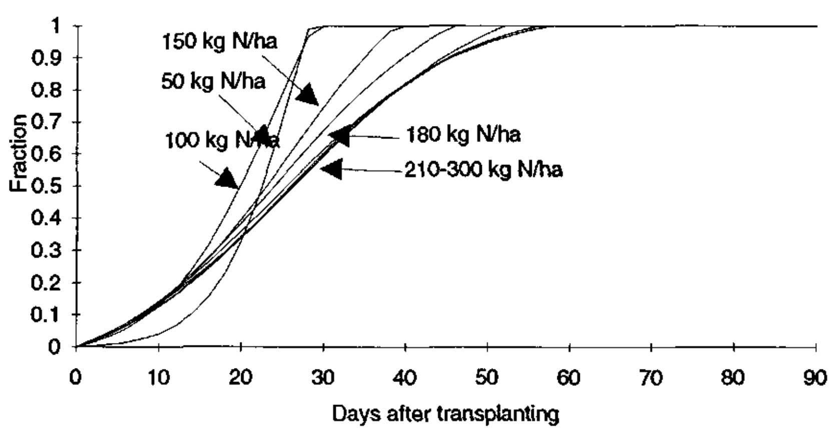

Figure 4. Recommended nitrogen fertilizer application curves corresponding to maximum biomass production. Calculated for cvar Xieyou 10 at Jinhua, late season 1993.

Conclusions

High N input resulted in a larger sink size (spikelet number per unit area) and increased leaf and stem biomass production, but did not increase grain yields. After calibrating the parameter *p* for preflowering and postflowering stages separately, the simulated biomass fitted rather well to observations. Variations in *p* merit further investigation. Combined with a numerical optimization procedure, ORYZA_0 generates recommendations of the amount and timing of fertilizer-N application needed to achieve maximum biomass or grain yield. These recommendations have to be tested in independent field trials. The simulated N response curve appeared to be realistic, and the recommendation curves indicate that different N management strategies should be followed for lower and higher N input levels.

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Numerical optimization of N fertilizer application to irrigated rice at Cuttack (India) in wet and dry seasons

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Introduction

In most rice soils application of fertilizer nitrogen is necessary to exploit the genetic potential of N responsive modern rice cultivars, grown with improved cultural practices. This is primarily so because the expansion of growing tissue and hence light interception of a rice crop is determined by the crop nitrogen status. The light use efficiency, too, and therefore the efficiency of rice production are affected by N supply to the crop.

The quantity and source of N fertilizer, and the method and timing of application decide the fate of nitrogen in the soil as well as in the crop. In many situations, fertilizer urea is a cheap source of nitrogen to rice. The application of split doses of broadcast urea to rice gives better results than the application of full basal dose at planting under irrigated condition. Deep placement of urea (prilled/super granules) in the soil minimizes loss of N and thus improves recovery of fertilizer N. But, simultaneously it is labour intensive and is not yet accepted by the Indian farmers. The waterlogged soils under intermediate, semi-deep and deep water situations have excessive standing water in the field during the entire growth period which prevents split doses of fertilizer N application. Under irrigated conditions it is possible to maintain a minimum level of standing water for rice during the crop growth period such that application of split doses of fertilizer N at different times is feasible. It is, then possible to optimize N application with respect to its dose, timing and splits.

Agricultural research and development is concerned with providing management information and viable options to farmers to enable them to make better decisions. Traditionally, fertilizer recommendations are made to farmers on the basis of factors such as location, soil type and farming system. Information from a wide variety of sources is used in formulating such recommendations, but field research results play a critical role. Field trials are generally replicated over a limited number of seasons in different locations and recommendations are made on the basis of best average performance. Over last few years, information technology has been introduced to broaden the extrapolation domain of empirical findings.

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The use of crop growth simulation models allow evaluation of alternative nutrient management strategies. Modelling helps to analyse risks and benefits of management strategies, and enables yield forecasts for different agroclimatic regions. In the present study the ORYZA_0 model of SARP (ten Berge et al., 1994) has been used for optimizing N fertilizer application to irrigated rice at Cuttack, India. The study includes (1) Quantification of N limited rice production in crop and soil parameters; (2) Numerical optimization of N fertilizer management; (3) Yield gap analysis; (4) Analysis of model performance by comparison with actual yields obtained in a long term trial.

Materials and methods

Experiments

Three field experiments were conducted during the wet season (July-December), 1991, and the dry seasons (January-May) of 1992 and 1993 at the Central Rice Research Institute, Cuttack (20.5° N, 86.5° E), India, to study the growth, yield and N uptake by irrigated rice. The experiment site was situated in the Mahanadi river delta. The soil was of clay loam texture and classified as a Typic Haplaquept with a pH of 6.1. Treatments consisted of different timing and rate of N fertilizer application for each of the experiment. The highest N rate was 200 kg N ha-1. A control treatment (no N) was also included in each experiment. The seedling ages of cvar IR36 at the time of transplanting were 30 d (1991), 21 d (1992) and 33 d (1993) and the spacings were 15 ′ 15 cm, 20 ′ 10 cm and 15 ′ 15 cm, respectively. The dry weights of leaves, stems, roots, panicles and grains were determined at variable intervals during the crop growth period. The N content of all plant organs were also determined using the micro-Kjeldahl distillation method. Per plot, a 5 m2 area was used to determine the final straw and grain yield. The details of these three experiments were reported by Dash et al., 1994 and Rao et al., 1994. Key dates are given in Table 1. The data sets of these three experiments were used to determine the input parameters for the model ORYZA_0.

Table 1. Dates of transplanting, first flowering and maturity of the crops in the experiments of 1991, 1992 and 1993, Cuttack, India. (DAT = days after transplanting).

	Wet season	Dry season	
	1991	1992	1993
Date of transplanting	11/09/91	28/01/92	28/01/93
Date of first flowering	62 DAT	68 DAT	65 DAT
Date of maturity	98 DAT	108 DAT	94 DAT

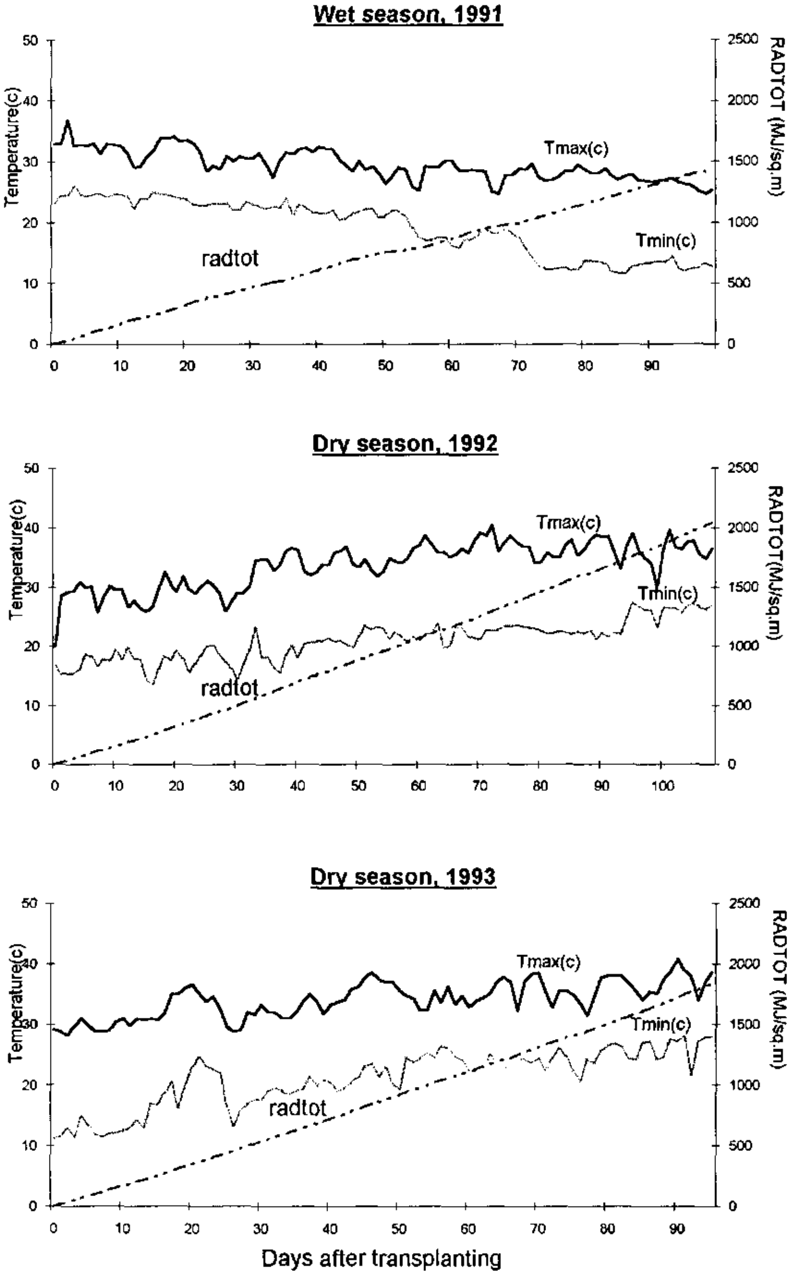

Figure 1. Daily maximum (Tmax) and minimum (Tmin) temperature (°C) and cumulative radiation (RADTOT, MJ m^{-2}) during the three experimental crop periods at CRRI, Cuttack, India. The planting dates were 254, 28 and 28 (Julian date) in 1991, 1992 and 1993, respectively.

In addition to above three experiments there were regular long-term experiments at the same experimental site where N response by different genotypes was studied in the wet seasons from 1987 to 1993. In these experiments, the N levels were 0 to 120 kg N ha^{-1} and more than 35 cultivars of different durations were tested for their response to N. They were of short (100-115 d), medium (120-135 d) and long duration (145-165 d). Planting was always in flooded soil in July, with a spacing of 15 × 15 cm. The age of the seedlings was 25 d for short, 30 d for medium and 35 d for long duration varieties. The dates of transplanting, flowering and harvesting at maturity were recorded for each. The biomass accumulation, grain and straw yields were determined in all treatments.

The model

The model ORYZA_0 simulates biomass accumulation in rice as limited by N uptake and daily total global radiation and can be used with numerical optimization to identify the best N fertilizer application curve for a given total amount of N input, and for specified varietal and environmental characteristics. For the present, it uses a fixed harvest index to convert biomass to grain production.

All the input data for the model were derived from the experiments. The efficiency factors FSV1 and FSV2 were determined by calibration of the model by matching simulated vs. observed time courses of biomass.

To convert the observed radiation from hours of sunshine duration to global radiation, we used the values of 0.25 and 0.45 for conversion parameters a and b respectively. The weather data are given in Figure 1.

Results and discussion

Quantification of crop and soil parameters

The different crop and soil parameters obtained from the three experiments are given in Table 1. Wide differences between seasons were noticed in several parameters. However, the fraction total crop nitrogen in leaves before flowering (FNCLV) was the same (0.55) under wet and dry season conditions. The maximum daily nitrogen uptake rate (MAXUP1) was higher in dry season than in wet season. There was not much difference in the N content of panicles (FNSO) at maturity under different seasons. The total amount of N in leaves (ANLVMX) was, however, different for different experiments. The maximum ratio of daily N uptake to growth (NUPCO) and relative N uptake rate (RUR) during first 30 days were highest in the dry season 1992. A constant harvest index was found in wet season 1991 and dry season 1992 whereas it was higher in dry season 1993. The recovery of N by the crop from the fertilizer (RECT) was higher in dry than in dry season conditions. The native soil N supplying rate (SOLSUP) was around 0.6 to 0.7 kg N ha^{-1} d^{-1} for one site (1991 and 1993 experiments) and 0.9 kg N ha^{-1} d^{-1} for the second site. These variations show that season and native soil fertility influence N uptake, even under condition of ample N supply. The match factor FSV reflects the overall efficiency of light and nitrogen utilization by the rice crop. The FSV values found in our experiments with IR36 are included in Table 2. It was found that the FSV values were lower in wet season than in dry

Table 2. The values of crop and soil input parameters derived from three experiments for rice cvar IR36 at Cuttack, India. These inputs values were used in the optimization of the N application curves.

Parameter	Value			Unit
	Wet season	Dry season		
	1991	1992	1993	
Crop parameter				
FNSO	0.012	0.012	0.016	g g^{-1}
FNCLV	0.55	0.55	0.56	g g^{-1}
ANLVMX	55	110	53	kg ha^{-1}
MAXUP1	3.6	5.5	4.7	kg N ha^{-1} d^{-1}
NUPCO	0.049	0.07	0.028	kg N kg^{-1}
RUR	0.135	0.18	0.125	g g^{-1} d^{-1}
FNMAXT	0., 0.026	0., 0.026	0., 0.026	g g^{-1}
	20., 0.044	22., 0.049	39., 0.025	
	55., 0.025	45., 0.028	48., 0.019	
	98., 0.013	62., 0.021	62., 0.017	
		93., 0.014	69., 0.016	
		108., 0.010	95., 0.013	
HI	0.45	0.45	0.57	g g^{-1}
FSV1	0.6	0.8	0.7	
FSV2	0.4	0.8	0.7	
DATFSV	70	-	-	
Soil parameter				
SOLSUP	0.7	0.6	0.63	kg ha^{-1} d^{-1}
RECT	0., 0.00	0., 0.00	0., 0.00	g g^{-1}
	40., 0.65	20., 0.55	20., 0.55	
	55., 0.27	40., 1.00	40., 1.00	
	75., 0.10	80., 1.00	80., 1.00	
	99., 0.00	85., 0.00	95., 0.00	
		108., 0.00		

DAT = days after transplanting

season. Besides, 70 days after transplanting, the FSV value decreased in the wet season but not in the dry season. The FSV value was slightly higher in the dry season of 1992 than in dry season of 1993. The differences in FSV values in different experiments might be associated with the differences in radiation or temperature. Cumulative and mean radiation in the wet season were lower than the dry season. Radiation was measured as daily sunshine duration (hours) and these values were converted to MJ m^{-2} d^{-1}. The values of

Table 3. The maximum and minimum temperature during the crop growth period under wet and dry season conditions.

Weather condition	Temperature (°C)			
	Pre-flowering		Post-flowering	
	Range	Mean	Range	Mean
Maximum temperature				
Wet season, 1991	25-37	31.2	25-30	27.4
Dry season, 1992	20-39	31.9	36-39	36.6
Dry season, 1993	28-39	33.6	32-41	36.3
Minimum temperature				
Wet season, 1991	16-25	22.5	12-19	14.0
Dry season, 1992	14-24	19.2	21-27	23.8
Dry season, 1993	11-26	19.5	21-28	25.1

Table 4. Crop N uptake in cvar IR36 under wet and dry season conditions at Cuttack, India, under high N supply.

Weather condition	Maximum N uptake (kg ha^{-1})			Soil N supply capacity (kg ha^{-1})		
	Pre-flowering	Post-flowering	Total	Pre-flowering	Post-flowering	Total
WS, 1991	120.1	8.0	128.1	57.8	0.0	57.8
DS, 1992	198.5	52.3	250.8	70.9	24.9	95.8
DS, 1993	132.2	39.4	171.6	56.6	17.5	74.1

these conversion factors (a, b) on cloudy days during wet season need further confirmation. The low post-flowering FSV value found in the wet season may be associated with low temperatures (Table 3), but this too needs further investigation.

The maximum N uptake capacity observed in the three experiments is given in Table 4. In the wet season there was reduced absorption up to flowering and also after flowering.

Very high amounts of N were absorbed in the dry season, even after flowering, increasing the current photosynthetic activity and thus biomass accumulation. In the wet season, very little N was absorbed after flowering.

The maximum leaf N and maximum crop N (FNMAXT) concentrations at various days after transplanting under wet and dry season conditions are presented in Figure 2. In the dry season 1992, the leaf N concentration was high throughout the growth period, whereas in dry season 1993 it remained lower. This was reflected in lower photosynthesis and dry matter production. The higher N concentration in wet season 1991 could be due to the

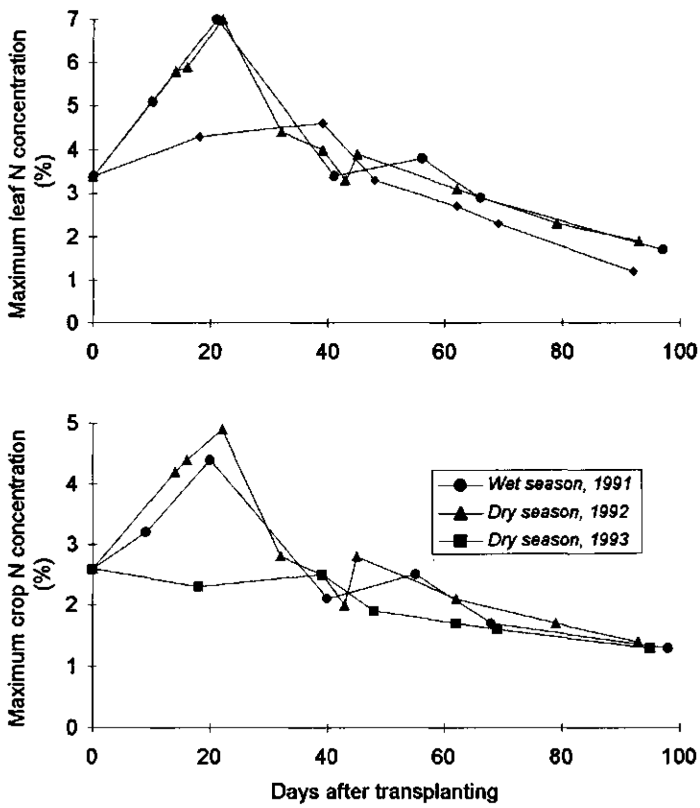

Figure 2. Maximum N concentration observed in the leaves and the crop biomass, in relationship to days after transplanting. Seedling age was 30 d (1991), 21 d (1992) and 33 d (1993) at the time of transplanting. Rice cvar IR36, Cuttack, India.

relatively low radiation level and the associated low biomass production. The maximum crop N content during different growth stages (FNMAXT) is depicted in Figure 2.

The soil N supplying capacity to rice plant during pre-flowering and post-flowering period is given in Table 4. The 1992 experimental site was fertile than the site used in other years. Besides, the seedlings used in 1992 were younger (21 d) which may have enhanced uptake.

Numerical Optimization of N Fertilizer Management

Response to application of fertilizer N

The maximum attainable biomass accumulation upon application calculated for selected total N input levels is presented in Figure 3 for the three experiments. For each of the three environments, a separate corresponding set of parameters (Table 2) was used. The shape of the response curve was very similar in each case, though the levels for different seasons are different. During the dry season 1992 the experimental site was different from the wet season 1991 and dry season 1993. The simulated biomass in the zero N treatment was 6.64 t ha^{-1} under wet season condition and 7.89 to 8.12 t ha^{-1} under dry season conditions. The biomass accumulation was higher in dry season condition due to higher FSV1 and FSV2 values (Table 2) and due to the higher radiation levels.

The maximum simulated biomass (10.4 t ha^{-1}) accumulation occurred at the level of 250 kg N ha^{-1} in the wet season. Under dry season conditions the highest simulated biomass (15.9-23.6 t ha^{-1}) was produced at N input levels exceeding 300 kg N ha^{-1}. Maintaining a harvest index of 0.45 in all cases these values correspond to grain yields of 4.7 t ha^{-1} in the wet season and 7.5 to 10.0 t ha^{-1} in the dry season. In view of these graphs, the current recommendation levels (60 and 80 kg N for wet and dry season conditions) seem to be rather low, but there may be a rationale behind these values which merits further inspection.

Timing of fertilizer N application

The optimal timing of N application is expressed in the N fertilizer application curves (Figure 4). These curves were derived by numerical optimization and were scaled relative to the total input level of 20 to 300 kg N ha^{-1}. They indicate that most of the fertilizer N (around 70-80%) should be applied before 30 to 35 DAT in the wet season and before 30 to 40 DAT for dry season at all the N input levels. This coincides roughly with the panicle initiation stage of the crop. In 1993, the recommended application curves were slightly earlier than in 1992. This may be related to the slightly bigger seedlings in 1993, but may also be affected by the lower soil N supply at the experimental site used in 1993.

In the existing practice, in a three equal split dose system, 50% of fertilizer N input is applied as a basal dose and the remaining 50% in two equal splits at active tillering stage and panicle initiation stages. Figure 5 shows the recommended dates for split applications, where a scheme of three equal splits was assumed.

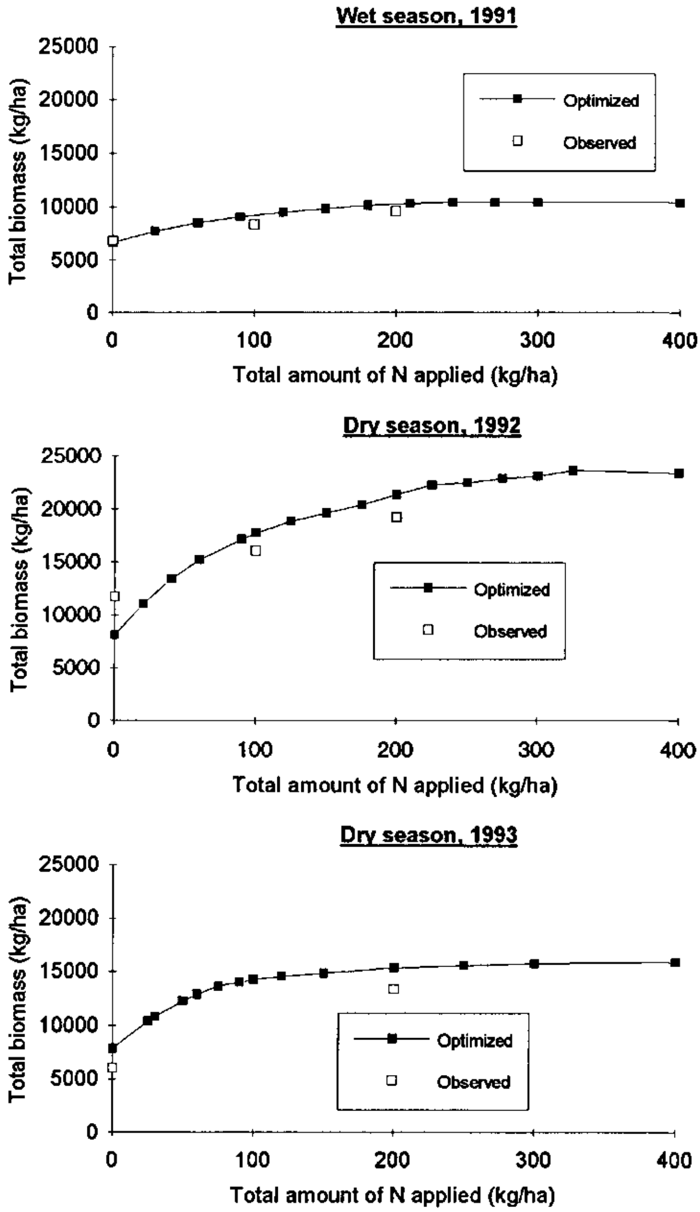

Figure 3. Simulated maximum response of cvar IR36 to N application under wet and dry season conditions in Cuttack, India.

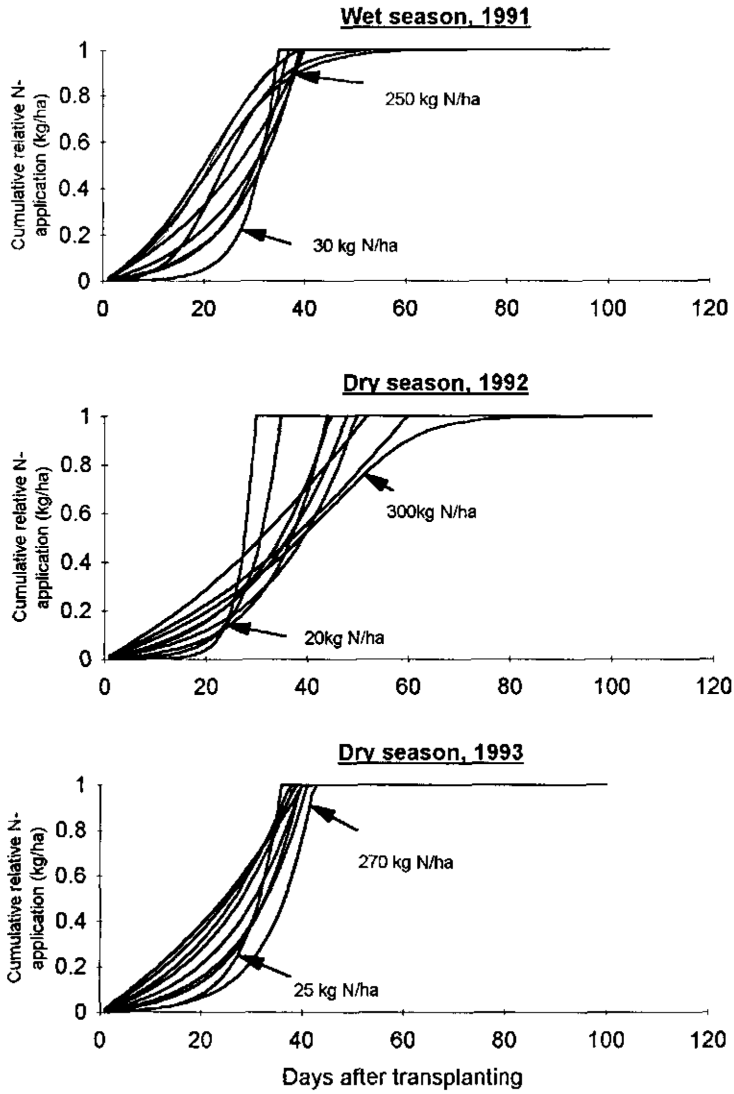

Figure 4. Recommended timing of the relative N application for cvar IR36 at various levels of N under wet and dry season conditions in Cuttack, India.

The optimum dose of N application in wet season and dry season has been fixed at 90 and 120 kg N ha^{-1}, respectively after optimization. The fertilizer recommendation curve corresponding to these application levels are given in Figure 6. It shows that optimum time of N application in three equal splits could be 46, 54 and 67 days after sowing for the first, second and third split doses, respectively, in the wet season. Similarly, for the dry season, the timing of fertilizer application is 45, 60 and 70 days after sowing for first, second and third split doses, respectively, at these recommended levels.

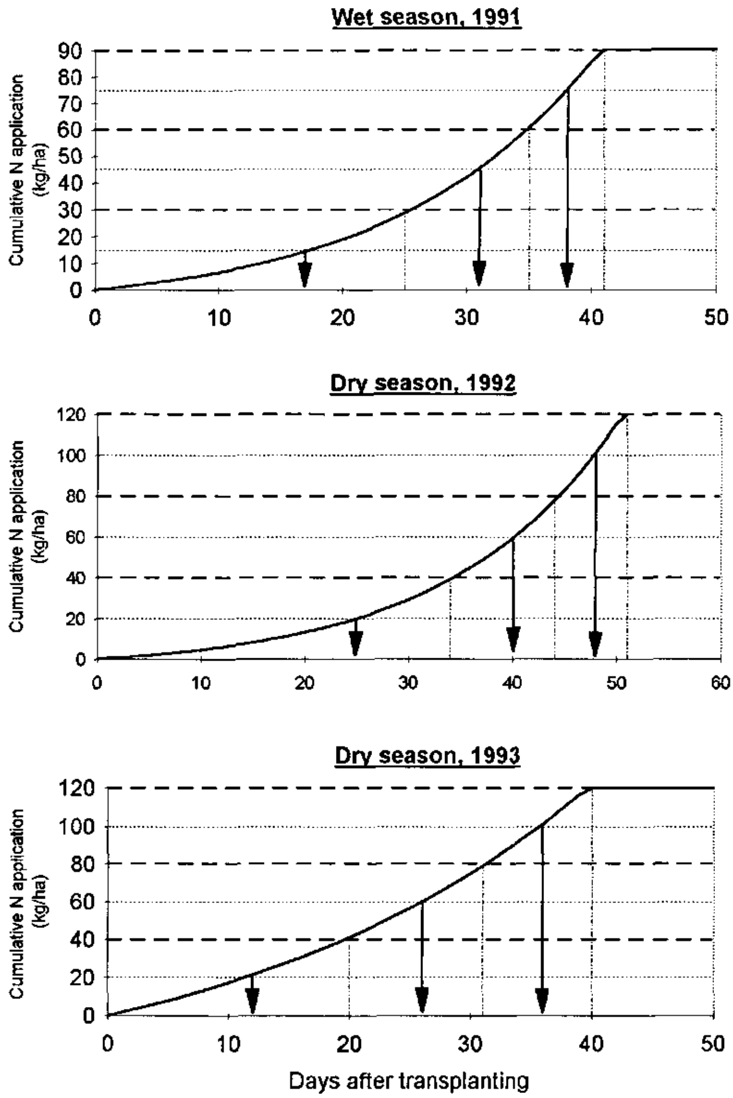

Figure 5. Timing of fertilizer N application for selected total input levels. A system of three equal split doses was presumed here for cvar IR36 under wet and dry season conditions at Cuttack, India.

A comparison was made between the computer based recommendation and the existing practice of fertilizer N application with respect to its dose, timing and splits (Table 5). A input level higher than used in current practice can be useful if combined with appropriate timing. The crop can then absorb more fertilizer N and can utilize it effectively. These recommendations have to be evaluated in comparative yield trials.

Table 5. N application schemes according to the state recommendation and the computer recommendation.

	Dose	Time of N fertilizer application (DAT)					
		State recommended splits (kg N ha^{-1})			Computer recommended splits (kg N ha^{-1})		
	(kg ha^{-1})	1st	2nd	3rd	1st	2nd	3rd
<u>State recommended</u>							
Wet season	60	Basal	21DAT	PI	23	32	37
Dry season	80	Basal	21DAT	PI	16	24	37
<u>Computer recommended</u>							
Wet season	90		-		16	24	37
Dry season	120		-		12	27	37

DAT = days after transplanting

PI = panicle initiation

Table 6. The yield gap attributable to the postflowering decrease of FSV for cvar IR36 at selected N input levels. Simulated for wet season. Assumed harvest index is 0.45.

N level (kg ha^{-1})	Biomass production (t ha^{-1}) FSV			Grain yield (t ha^{-1}) FSV		
	0.6	0.6 & 0.4	Gap	0.6	0.6 & 0.4	Gap
0	7.35	6.64	0.71	3.31	2.99	0.32
30	8.67	7.75	0.92	3.90	3.49	0.41
60	9.54	8.51	1.03	4.29	3.83	0.46
90	10.22	9.07	1.15	4.60	4.08	0.52
120	10.74	9.50	1.24	4.83	4.28	0.55
150	11.12	9.84	1.28	5.00	4.43	0.57
180	11.35	10.15	1.20	5.11	4.57	0.54
210	11.56	10.21	1.35	5.20	4.59	0.61
240	11.64	10.33	1.31	5.24	4.65	0.59
270	11.64	10.42	1.22	5.24	4.69	0.55

FSV = site variety specific match factor

Yield Gap Analysis

The FSV values remained constant throughout the growth period under dry season conditions at Cuttack. However, under wet season condition FSV attained very low values after flowering. This might be attributed to low minimum temperatures in the range of 12-19°C which may partially inhibit translocation of carbohydrates (Ishizuka et al., 1962). Table 6 compares biomass and grain yields attainable if FSV would maintain a fixed value

(0.6) versus the attainable values for the case where FSV drops from 0.6 (preflowering) to 0.4 (postflowering) as occurs in reality in the wet season. The difference between these respective values is expressed as a 'yield gap' which is attributable to the unknown factors underlying the postflowering shift in FSV. It quantifies the potential benefit from research aimed at halting the observed decline in FSV.

Testing of the Model Performance

The model with soil and crop parameters derived from 1991 wet season experiment for the variety IR36 was tested for several varieties grown during wet season 1987 to 1993 with actual time of transplanting, flowering and maturity. The output of the model was compared with the observed biomass of these cultivars at different input levels (Figure 6). There was a close agreement between the simulated and observed biomass across all the cultivars and N application levels. This suggests that the crop and soil parameters derived for the cultivar IR36 from the wet season 1991 data can be used to represent several other varieties of different durations grown in the wet season. There were three groups of cultivars based on their durations which were tested in the study. Among these three groups of varieties, the biomass of the varieties of the medium duration (125-135 days) was simulated best. The duration of these varieties was close to that of cvar IR36 for which the input parameters were derived and used in the simulations.

The yield gap analysis as presented in the previous paragraph (Table 7) was also applied to this set of long-term data. It was found that wet season rice yields would increase by 0.4-0.5 t ha^{-1} on average, if the FSV value could be maintained at 0.6 throughout the growth period. This was calculated under the assumption that harvest index would not change by increased postflowering growth resulting from increased FSV. As the harvest index would in reality also increase as a result of better postflowering growth, it can be safely stated that solving the problems which limit postflowering FSV values will increase grain yields by more than 0.5 t ha^{-1}.

Overview of the Harvest Index

The harvest index was different for varieties of different durations (Table 8). For short duration varieties (100-115 d) duration grown in the wet season the average harvest index was 0.47 where as for medium duration varieties of 120-135 days duration it decreased to 0.41. For long duration varieties the average harvest index was 0.38. The effect of different N application levels influencing the harvest index was also studied. It was found that at 0 kg N ha^{-1} the average harvest index was 0.42 which remained almost constant upto 60-80 kg N ha^{-1}. At higher level of N application (90-120 kg N ha^{-1}) the harvest index reduced to 0.39, though the biomass production increased.

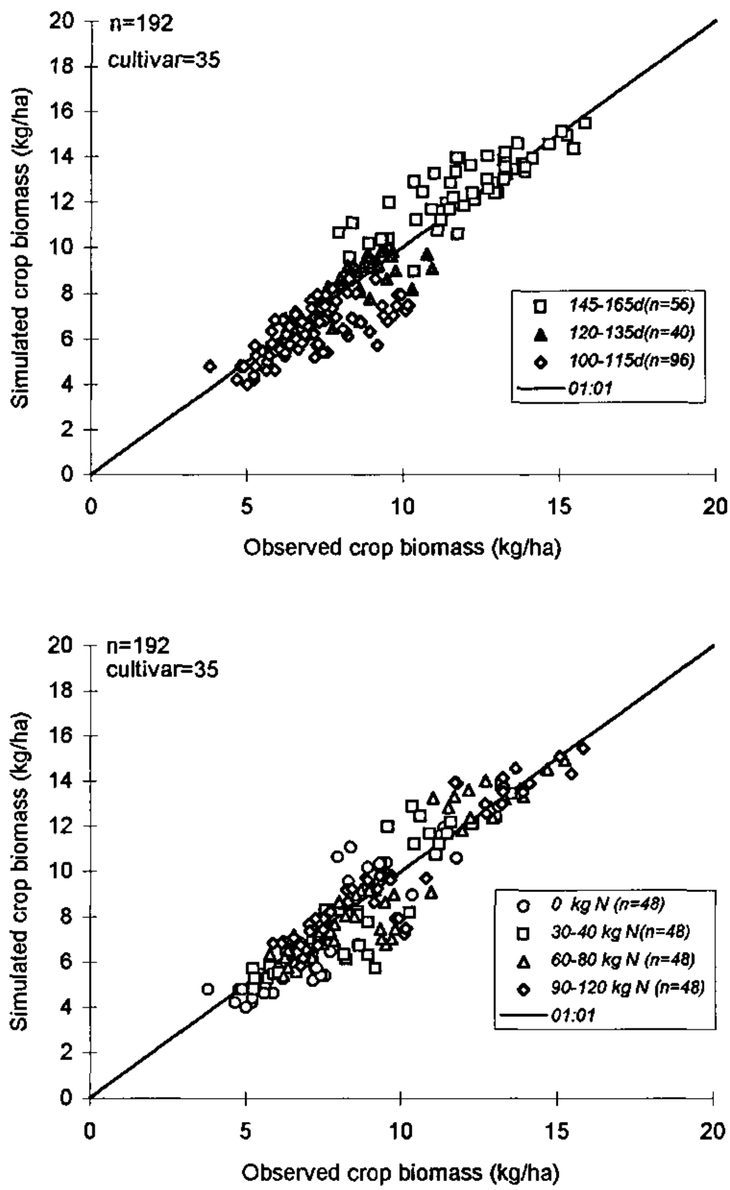

Figure 6. Relation between simulated and observed crop biomass of short, medium and long duration rice cultivars at different N application levels.

Table 7. The yield gap of different rice cultivars optimized at the level of 60-80 kg N ha^{-1} attributed to the postflowering decrease of FSV in the wet season, Cuttack, India (values are averages over duration groups. The grain yield gaps are derived from biomass gap assuming the harvest index of 0.45).

Duration	Biomass production (t ha^{-1})			Grain yield (t ha^{-1})		
	FSV		Gap	FSV		Gap
	0.6	0.6 & 0.4		0.6	0.6 & 0.4	
Long [145-165 d]	14.43	13.28	1.15	6.49	5.98	0.51
Medium [120-135 d]	10.09	8.95	1.14	4.54	4.03	0.51
Short [100-115 d]	7.77	6.82	0.95	3.50	3.07	0.43

FSV = site variety specific match factor

Table 8. Harvest Index of several rice cultivars as affected by crop duration and N levels in wet season.

Duration	N level (kg ha^{-1})				Mean
	0	30-40	60-80	90-120	
Long [145-165 d]	0.38	0.39	0.38	0.36	0.38
Medium [120-135 d]	0.41	0.41	0.42	0.39	0.41
Short [100-115 d]	0.48	0.48	0.47	0.43	0.47
Mean	0.42	0.43	0.42	0.39	

As a result of these observations, the ORYZA_0 model has been adapted and now expresses harvest index as a function of biomass at flowering and postflowering cumulative radiation.

Conclusions

1. The N uptake capacity of rice variety IR36 under ample N supply was very much influenced by the season and site. Seasonal effect may be attributed to weather conditions such as radiation. Site effects may be attributed to the native soil N supply rate.
2. The maximum daily nitrogen uptake rate was 3.6-5.5 kg N ha^{-1} d^{-1} and it was usually higher in the dry season than in the wet season.
3. The fraction of total crop nitrogen that was stored in leaves was usually 0.55 before flowering and did not change between wet and dry season conditions.
4. The recovery of fertilizer N was higher in the dry season than in the wet season.

5. In the wet season very little N was absorbed by the crop after flowering whereas very high amounts of N could be absorbed after flowering in the dry season.
6. The site variety specific match factor (FSV) for cultivar IR36 was higher in the dry season; moreover it decreased further after flowering.
7. An application of 90 kg N ha^{-1} in 3 equal splits at 46, 54 and 67 days after sowing for the variety IR36 in the wet season and 120 kg N ha^{-1} in three equal splits at 45, 60 and 70 days after sowing in the dry season is recommended for Cuttack on the basis of simulation modelling. These levels of N application are higher than the current recommended levels, but may be effective only when combined with appropriate timing.
8. Based on available radiation and leaf nitrogen in the wet season, postflowering biomass accumulation could be higher by about 1 t ha^{-1} and grain yield by about 0.5 t ha^{-1}. The causes of this gap are unclear at present.
9. There was a close agreement between the wet season simulated and observed yields of several medium duration varieties at different N application levels. Best agreements were found at optimum level of N application. Only one set of crop parameters (IR36) was used in making the predictions for all varieties.
10. The harvest index of short duration rice varieties (100-115 d) was higher than the medium and long duration varieties grown in the wet season, and decreased slightly with N application.

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Use of ORYZA-0 model in integrated N management system

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Introduction

Rice constitutes the principal source of food for a large populations of the world. In India, the demand for rice is projected to be 96 Mt in 2000 to feed the increased population and has to be produced from 41 Mha of paddy land (Sampath, 1990). Nitrogen is the primary factor in increasing the grain yield of rice. In South and Southeast Asia, low recovery of fertilizer N applied to rice, its high cost, low price of rice grain and the low purchasing power of the farmers are some of the important constraints to keep the rates of N application to rice low (Prasad & De Datta, 1979). Under these circumstances, research on the use of organic materials, at least to partially substitute fertilizer N in rice production, has been intensified in the recent past. In this context, green manure's offer a potential as a substitute for fertilizer N and may stabilize the income of the rice farmers on a sustained basis.

A field study was undertaken to compare rice response to different N sources and N levels. The model ORYZA-0 (ten Berge et al., 1994) was used to analyse the results and to derive optimum N application timing and to determine attainable yield levels under current conditions in Cauvery delta zone of Tamil Nadu, India.

Materials and methods

Field experiment

Two field experiments were conducted at Tamil Nadu Rice Research Institute, Aduthurai, India (11° N latitude, 77° longitude and 19 m altitude) during the wet season (August-December) of 1992 and 1993. The soil was classified according to Soil Taxonomy (Soil Survey Staff, 1975) as a fine Chromustert of clay loam texture. The experiment consisted of eight fertilizer/green manure N treatments (Table 1) and was conducted in a randomized block design with four replications using plots of 9×4m which remained flooded throughout the experiment.

The fertilizer N source was urea (46% N) and the green manure N source was *Sesbania rostrata*. All treatments received 60 kg each of P_2O_5 and K_2O ha^{-1}. The full dose of P was

Eds. T.M. Thiyagarajan, H.F.M. ten Berge & M.C.S. Wopereis. Nitrogen management studies in irrigated rice. SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen and IRRI, Los Baños (1995), pp 27-37.

applied basally at the time of transplanting and K was applied in three equal splits at planting, active tillering and panicle initiation stages. *Sesbania rostrata* was grown and 50 d old plants were harvested for incorporation. The N content (Kjeldahl method) of *Sesbania rostrata* was 4.36 and 4.52% in 1992 and 1993 respectively. Green manure was applied a day before the rice was transplanted. Urea was topdressed in five equal splits i.e., at the time of transplanting, active tillering, maximum tillering, panicle initiation and flowering. The test variety was ADT38, a medium duration (135 d) cultivar. Seedlings (34 d old in 1992 and 30 d old in 1993) were transplanted on 16.09.1992 (calendar day 260) and 13.9.93 (calendar day 256) in puddled soil, using one seedling per hill and adopting a plant spacing of 20 × 10 cm (50 hills m^{-1}). Plant samples were collected periodically to determine the biomass of plant organs i.e. leaf, stem, root and panicle, and also for N determination. Adequate crop protection measures were taken throughout the experiment.

Table 1. N treatments in the field experiment (Aduthurai, Wet season, 1992 and 1993).

Treatment	Urea N	Green manure N	Total N
	kg ha^{-1}		
T1	100	-	100
T2	50	50	100
T3	-	100	100
T4	200	-	200
T5	100	100	200
T6	-	200	200
T7*	150	72 **	222
T8	0	0	0

* Recommended practice

** 6.25 t ha^{-1} green manure

The model

The simulation model ORYZA_0 (ten Berge et al., 1994) was used in the present study to determine the efficiency by which leaf N and radiation were used to produce dry matter in the respective treatments, and to assess optimum N application schemes by numerical optimization.

The key crop and soil parameters were derived from field experiments during 1992 and 1993. The mean values of crop and soil parameters/functions from both years were used. The optimization procedure was repeated for each of six N input levels : 50, 100, 150, 200, 250 and 300 kg ha^{-1} (total N input). The highest level was included only to verify that indeed a plateau is reached. The above procedure was repeated for both years.

Results and discussion

Crop N uptake

Crop N uptake was significantly influenced by the sources and levels of N. In both years, the crop N uptake in fertilizer N at 100 kg ha^{-1} was similar to that in green manure N at 200 kg ha^{-1} and integrated N source at 100 kg ha^{-1} (Figure 1). Leaf contributed to more crop N uptake at active tillering and panicle initiation while stem contributed more at flowering and harvest stages. In general, amounts of N in the leaf, stem and root was increasing steadily upto flowering and declined thereafter. After flowering, translocation of N from the vegetative organs to the grains became significant. There was some translocation of carbohydrates from vegetative plant parts to the grains.

The increased N uptake at high N application levels and with integrated N sources was expressed both in increased N concentration in plant parts (viz., leaf, stem, root and panicles, Table 2) and in increased biomass and yield attributes. Increasing the yield through increased N uptake by combining green manure and fertilizer N would be beneficial if N supplied through is economical.

Role of ORYZA_0 in studying the utilization of N by rice

The crop and soil parameters used in the model are presented in Table 3. The value of parameter *p* was obtained by fitting simulated to observed time courses of biomass. The closeness of fit was satisfactory from transplanting to flowering (pre-flowering) in both the years. However, from 2-3 weeks after first flowering onward, the measured biomass accumulation in both the years was lower than simulated values. Net growth virtually ceased beyond this stage, while a steady growth could still be maintained based on available leaf N and radiation. In other words, the leaf N efficiency factor p decreased drastically from 9 g g^{-1} d^{-1} to less than half this value. Although this has been observed in several other cases (locations/seasons), it is certainly not common. The value of this leaf N efficiency factor was independent of the treatment i.e. fertilizer level or N source. Hence it is clear the crop growth depends mainly on the uptake pattern (leaf N uptake) and not on the source from which N was derived.

Experiments conducted with different cultivars viz., IR36, IR64, IR72, MR1 and ASD16 in various countries revealed that the biomass production continued till the harvest of the crop (Singh et al., 1987; Palanisamy et al., 1989; Dash et al., 1994; Rao et al., 1994; Makarim et al., 1994; Daradjat et al., 1994; and Wopereis et al., 1994). In all the above cases harvest index was around 0.5. In the present study, the total biomass production decreased 2-3 weeks after first flowering (Figure 3). It was assessed by simulation that the grain yield loss caused by the postflowering decrease of the leaf N efficiency factor *p* amounted to 2.5 - 3.5 t ha^{-1}, depending on N application level. (These figures were calculated on the basis of actually observed radiation and leaf N time courses).

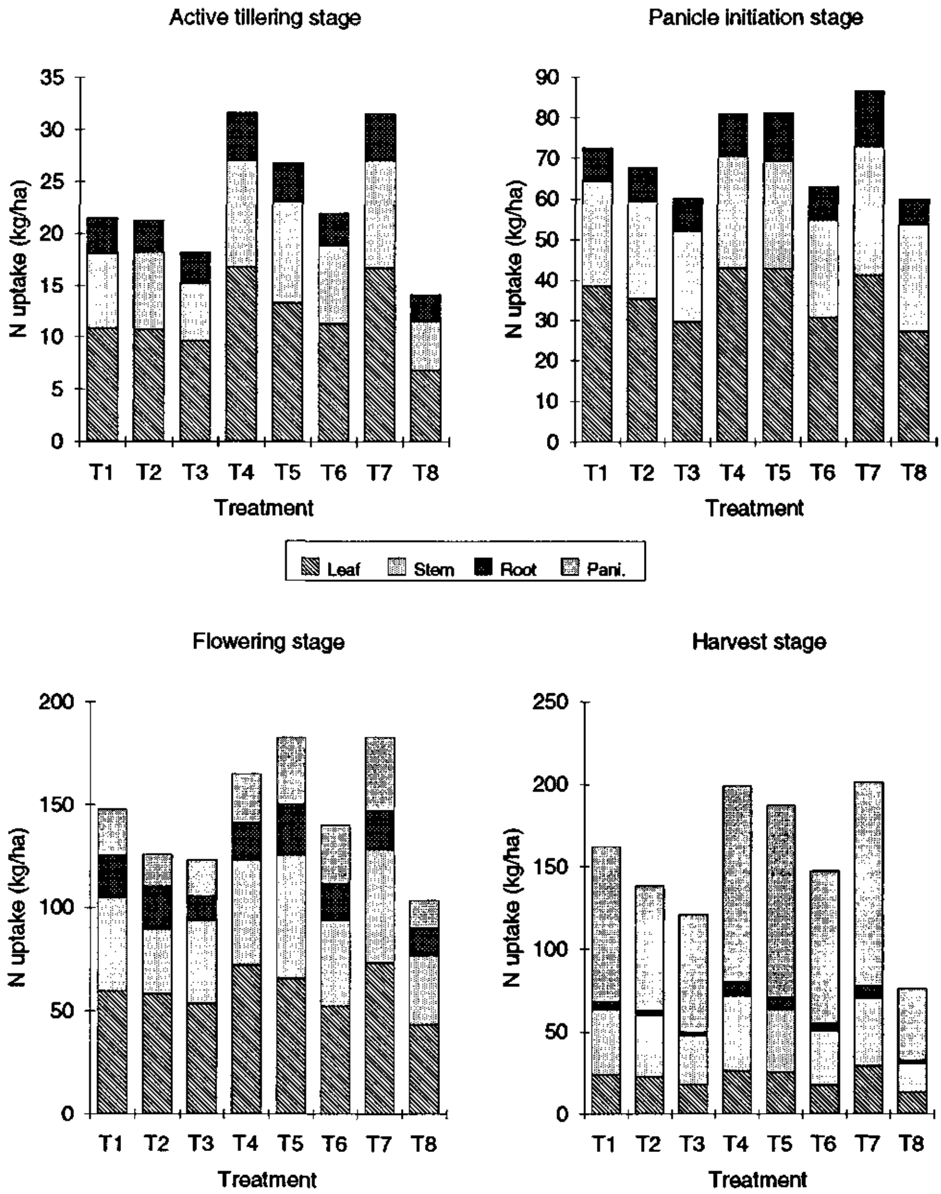


Figure 1. N uptake in the plant organs at different growth stages of rice cvar ADT38, Aduthurai, India, wet season, 1992 and 1993. Explanation of treatments T1-T8 is given in Table 1.

Table 2. N concentration (g kg^{-1}) in plant organs at different growth stages of rice cvar ADT38, Aduthurai, India, wet season 1992 and 1993.

1992

Treatment	AT			PI			FL				HA			
	Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root	Pani.	Leaf	Stem	Root	Pani.
T1	40.1	31.2	17.7	32.5	23.8	13.8	21.9	12.4	9.1	14.1	11.3	8.8	4.4	14.6
T2	41.8	28.9	17.2	34.1	22.8	14.5	22.7	13.0	7.1	10.7	11.8	8.8	3.0	15.7
T3	41.2	26.7	19.1	29.0	22.5	14.6	21.0	7.4	8.8	13.5	8.8	7.4	1.8	12.1
T4	50.7	33.8	22.4	35.6	23.6	15.8	21.9	10.9	10.4	13.2	11.2	9.0	6.8	16.4
T5	42.9	32.8	20.1	34.6	24.4	15.7	21.2	12.2	11.0	16.6	9.8	8.5	5.4	15.7
T6	42.4	30.6	17.7	29.3	22.7	13.5	19.4	11.2	8.8	16.0	7.4	7.2	4.4	14.6
T7	49.3	31.4	20.5	34.0	27.0	18.8	22.9	11.5	10.2	18.3	11.2	8.0	6.2	16.8
T8	36.2	27.2	16.6	29.0	26.6	12.9	19.8	9.4	8.5	12.7	7.3	4.3	2.2	10.4
SEd	1.6	0.7	1.2	3.2	0.8	0.8	0.7	1.0	0.6	0.8	0.6	0.4	0.6	1.0
CD	3.3	1.4	2.5	NS	1.7	1.6	1.4	2.1	1.2	1.6	1.3	0.9	1.4	2.1

1993

Treatment	AT			PI			FL				HA			
	Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root	Pani.	Leaf	Stem	Root	Pani.
T1	42.5	23.6	17.3	31.3	15.7	13.2	17.6	11.2	11.2	12.4	10.9	9.0	7.4	14.6
T2	41.5	23.0	17.6	30.6	17.0	11.5	16.1	12.1	11.0	11.9	10.5	10.1	6.0	14.9
T3	41.2	23.3	18.8	29.2	18.2	13.2	15.5	11.4	11.0	11.2	9.4	6.7	7.1	12.1
T4	42.9	25.8	17.7	32.2	22.4	15.4	17.9	12.2	11.4	13.2	12.4	10.6	8.1	14.0
T5	45.6	28.6	19.1	33.2	21.2	16.7	18.6	12.4	11.7	15.4	13.1	9.5	7.8	13.4
T6	42.2	24.6	19.7	31.0	15.1	12.3	17.6	11.2	11.1	12.6	10.6	7.3	8.5	14.0
T7	42.6	29.7	22.8	32.0	20.7	15.4	17.9	12.4	11.9	13.4	12.5	8.6	9.0	14.8
T8	40.7	22.2	16.7	25.4	14.0	10.9	14.8	7.8	9.9	11.6	8.2	5.6	5.5	11.2
SEd	0.9	3.2	1.4	0.7	1.0	1.3	0.5	0.5	0.7	0.5	1.2	1.0	0.4	0.5
CD	1.9	NS	2.9	1.4	2.1	2.6	1.0	1.0	1.4	1.0	2.6	2.0	0.8	1.0

AT: Active tillering PI: Panicle initiation
FL: Flowering HA: Harvest

Table 3. Input parameters and functions used in ORYZA_0 to derive the best attainable N response curve and the fertilizer recommendation curves. The parameter values are averages over 1992 and 1993 values.

Parameters description	Acronym	Value	Unit
Crop parameters			
1. Fraction of total crop N present in leaves	FNCLV	0.5	g/g
2. Relative N uptake rate	RUR	0.2	g/g/d
3. Fraction of nitrogen in panicle	FNSO	0.013	g/g
4. Maximum ratio of daily N uptake to growth	NUPCO	0.05	g/g/d
5. Maximum daily N uptake	MAXUP1	0.34	g /m²/d
6. Maximum N concentration(mean crop biomass) vs time at	FNMAXT		
	TP	0.027	g/g
	AT	0.036	
	PI	0.026	
	FL	0.016	
	HA	0.013	
7. Maximum amount of N in leaves	ANLVMA	85	kg/ha
8. Initial leaf N use coefficient	P	9.0	g/g/d
9. Initial global radiation use coefficient	EPSIL	3.5	g/MJ
10. Radiation effectivity coefficient	ALPHA	0.035	d/m/MJ
Soil parameters			
1. Native soil N supply	SOLSUP	0.72	g /m²/d
2. Fertilizer N recovery	RECT		g/g
	TP	0.0	
	PI	0.4	
	FL	0.45	
	HA	0.0	
Time parameters			
1. Date of transplanting	STTME	16/09/92	
		13/09/93	
2. Date of first flowering	DATFF	65	DAT
3. Date of maturity	DATH	105	DAT

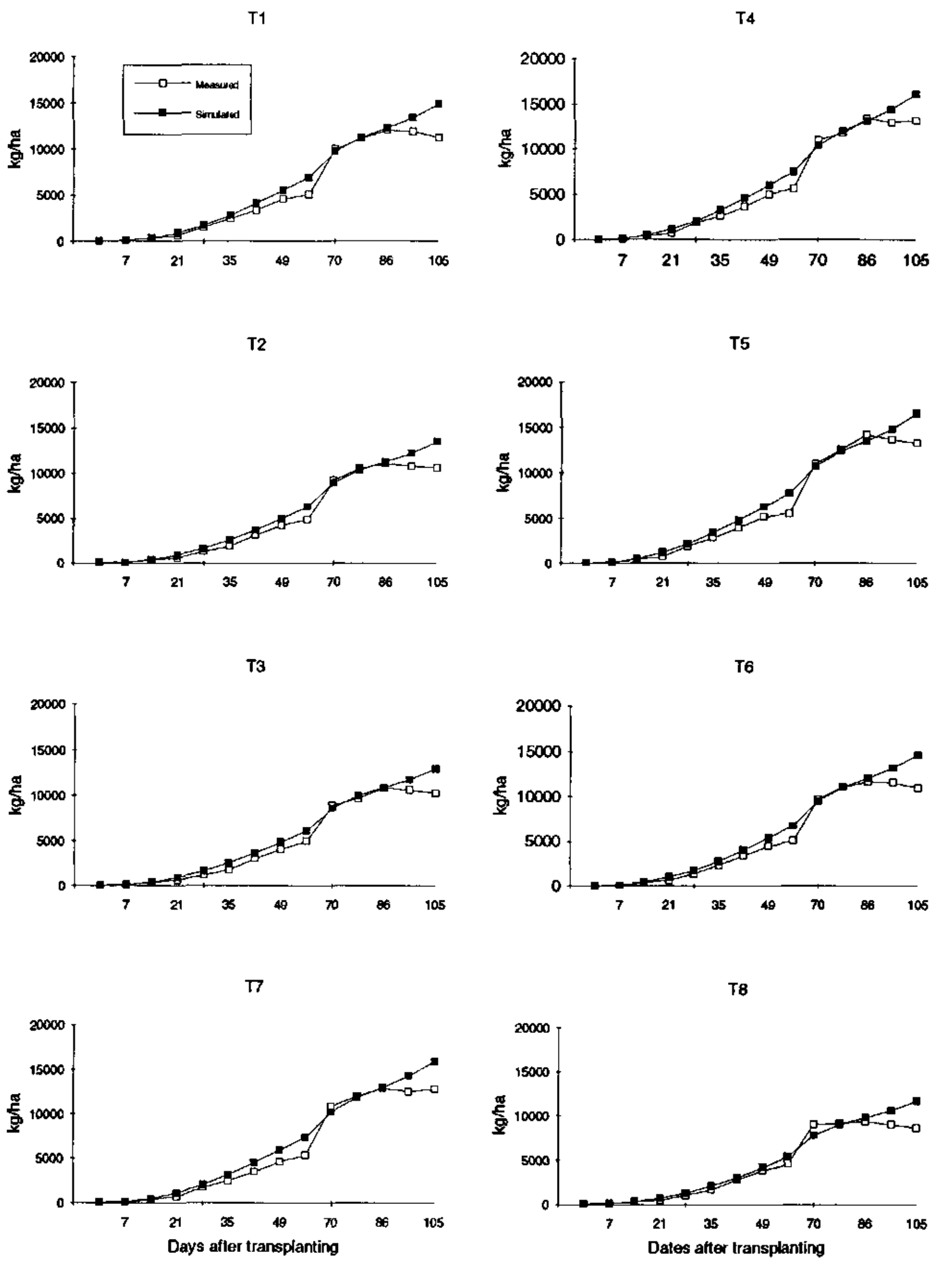


Figure 2. Measured and simulated biomass at different sampling dates. Aduthurai 1993. Explanation of treatments T1-T8 is given in Table 1.

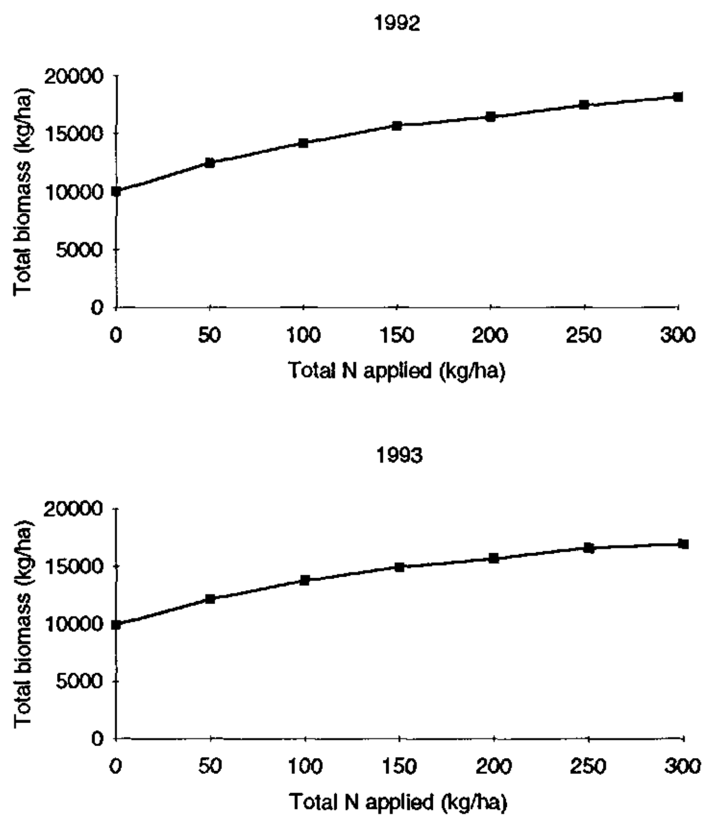
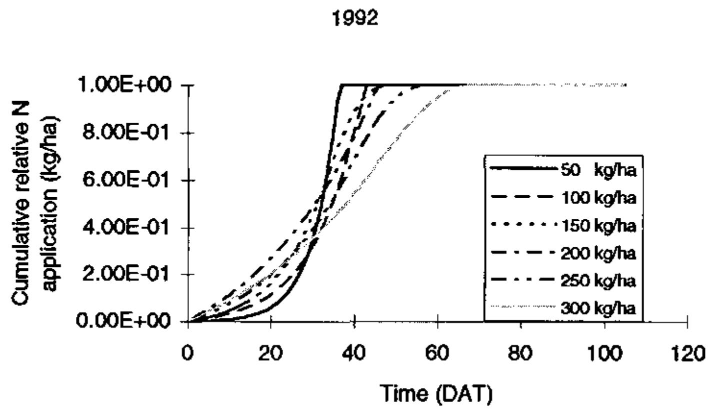


Figure 3. Maximum attainable total crop biomass production for cvar ADT38 at selected N input levels as simulated by the ORYZA_0 model, for 1992 and 1993. The curves were generated by optimization of the N application time curve for each of the N input levels. For input parameters see Table 3.

The fertilizer recommendation curves (Figure 4) indicate that at very high (300 kg ha^{-1}), high (250 kg ha^{-1}), medium (200, 150, 100 kg ha^{-1}) and low (50 kg ha^{-1}) N input levels, the total N application should be completed by 56-66 DAT, 50-56 DAT, 41-46 DAT and 36-38 DAT, respectively. In Tamil Nadu, there are two types of recommendation for N applications viz., 3 splits (50% at transplanting and 25% at active tillering and 25% at panicle initiation) and 5 equal splits (at transplanting, active and maximum tillering, panicle initiation and flowering stages). In the case of 3 splits, the model based recommendation resembles the actual practice for all the N input levels except at very high N level. In the case of 5 splits, the model based recommendation deviates from practice as the N application is to be completed by 46 DAT itself. The reason for this discrepancy between model based recommended timing and the timing in current farm practice with 5 split application merits further investigation.



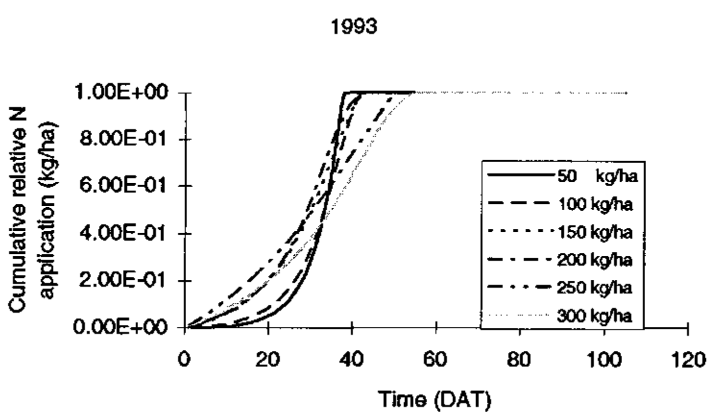


Figure 4. N fertilizer recommendation curves corresponding to maximum biomass production for cvar ADT38 simulated with the radiation data of 1992 and 1993. The curves were obtained by numerical optimization and are scaled relative to the respective total input levels.

Conclusions

1. Nitrogen application markedly increased the N uptake in the plant organs and total crop. Conjunctive use of N at 200 and 222 kg ha^{-1} and fertilizer N at 200 kg ha^{-1} recorded the maximum N uptake. The crop N uptake in was almost similar at input level of 100 kg N ha irrespective of the source of N and was also similar to that of 200 kg ha^{-1} as green manure N.
2. The leaf N efficiency factor p was not affected by treatments, indicating that, once N absorbed and allocated to leaves, its utilization by the crop in producing dry matter is independent of its source.
3. The postflowering decrease of leaf N efficiency at this site causes a yield loss of 2.5 - 3.6 t ha^{-1}. This phenomenon is not universal and demands further investigation.

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Field verification of model (ORYZA_0) recommended N application strategy for dry season rice in IRRI

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Introduction

The experimental information from several SARP teams about nitrogen (N) uptake and utilization by irrigated wet land rice crop enabled the development of a simple summary model (ORYZA_0), which could be used to derive the optimum application strategy for N fertilizer application under specified varietal and environmental conditions using numerical optimization techniques (ten Berge et al., 1994). This paper is about the results of a verification trial conducted at the experimental farm in IRRI, Los Baños, to evaluate the site tailored model recommendation in comparison with other current N application strategies.

Materials and methods

Field site

The field experiment was conducted at the International Rice Research Institute (IRRI) during the dry season (DS) 1994. The soil was classified as a mixed, isohyperthermic Typic Tropudalf (Soil Survey Staff, 1975). The experimental plot size was 4.0 x 7.0 m and the treatments were completely randomized in four replicates.

Treatments

The treatments consisted of different timing (0 to 3 splits) and rate (0 to 160 kg ha^{-1}) of N fertilizer as shown in Table 1.

Fertlizer N levels 120 and 160 kg ha^{-1} were applied with three application strategies i.e. previous IRRI recommendation (IRRI-old), current IRRI recommendation (IRRI-new) and model recommended (Model) timings. The IRRI-new recommendation has been based on empirical optimization over the past 4 years. The level of 120 kg ha^{-1} was based on the current IRRI recommendation for DS and the level of 160 kg ha^{-1} was chosen to test the effect of a higher dose of N. The N application vs. biomass response curve simulated by the model ORYZA_0 *version 1.0* was derived by using the data collected from the experiment conducted during 1993 (Wopereis et al., 1994). The splits and timing of splits for the model recommendation were derived from the cumulative N application curve as described by ten Berge et al. (1994). The grain yields were recorded at maturity.

Table 1. Fertilizer N application details.

Treatment	Strategy	Split number	Time of application	Rate of N (kg ha^{-1})	Total N applied (kg ha^{-1})
T1	Zero	-	-		
T2	Model	1	28 DAT	60	
		2	38 DAT	60	120
T3	IRRI- old	1	21 DAT	0	
		2	42 DAT	40	120
T4	IRRI-new	1	0 DAT	80	
		2	PI*	40	120
T5	Model	1	24 DAT	53.3	
		2	33 DAT	53.3	
		3	42 DAT	53.3	160
T6	IRRI-old	1	15 DAT	53.3	
		2	30 DAT	53.3	
		3	42 DAT	53.3	160
T7	IRRI-new	1	0 DAT	107	
		2	PI*	53	160

* PI = Panicle Initiation

Results and discussion

The grain yield data showed that there was not much difference between the three different timing of N applications as well as for the levels of application (Figure 1).

At 120 kg N ha^{-1}, the model recommendation was equally good as the new IRRI recommendation. At 100 kg N ha^{-1}, the new IRRI recommendation performed slightly better. Given the situation that the model recommendation is based on biophysical parameters derived from a single experiment at other N input levels, these results of the numerical approach are considered satisfactory.

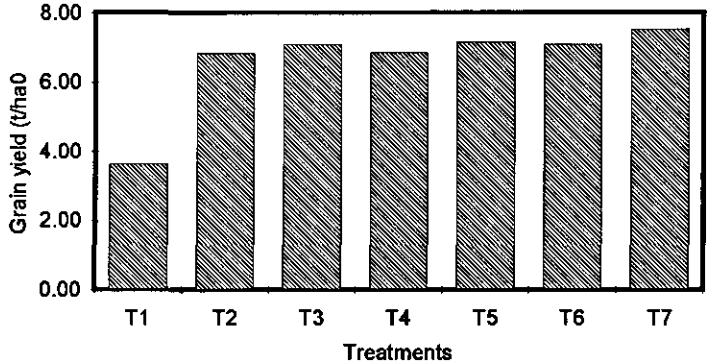

Figure 1. Grain yield of cvar IR72 at the different N application strategies. IRRI, dry season, 1994. Treatment codes are explained in Table 1.

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Effects of nitrogen application at heading and root activity on the grain yield of rice

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Introduction

Among the major plant nutrients, nitrogen is the most limiting one for rice production. The applied N in the puddled soil is subject to various loss processes (De Datta, 1981). Split application is necessary to meet the N demand at different growth phases. In heavy clay soils with high CEC, application of N in three splits viz., 50% basal, 25% each at tillering and panicle initiation stages is very common and in light textured tropical soils, where leaching is the predominant loss process, four splits is also common (Mongia, 1992). There are reports for and against N application at and after heading. In all these studies, the soil condition or root activity was not taken into consideration. Ramasamy (1992) found that higher N application and poor soil aeration, especially after panicle initiation negatively affected the grain filling process and grain yield. The present study was taken up to explore the effect of N application at the time of heading on the grain yield in relation to root activity.

Materials and methods

A field experiment was conducted at Tamil Nadu Agricultural University, Coimbatore (11 °N latitude, 77 °E longitude and 432 m above MSL) with two levels of drainage and these two were coupled with two levels of nitrogen top-dressing (Experiment 1, Table 1). A common dose of 120 kg N ha^{-1} was applied as 60 kg at planting, 30 kg at 20 DAT (mid-tillering) and 30 kg at 40 DAT (panicle initiation). Fifty kg each of P_2O_5 and K_2O ha^{-1} were applied at planting and incorporated. Seedlings of rice variety IR20 (a medium duration, 130-135 days, semi-dwarf, erect-stand, medium slender grain with yield potential of 5.0 t ha^{-1}) were transplanted (details in Table 2). A standing water layer of five cm was maintained on the field throughout the growth period until the grains turned golden yellow. Based on the results of Experiment 1 (EXPT1), a second experiment (EXPT2) was conducted with the objective to prolong the root activity (a special feature recorded in the open drainage (DW) treatment of the EXPT1) through some means other than drainage, since providing an open drainage is quite expensive and impractical under field conditions.

Eds T.M. Thiyagarajan, H.F.M. ten Berge & M.C.S. Wopereis. Nitrogen management studies in irrigated rice. SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen and IRRI, Los Baños (1995), pp 43-53.

Table 1. Treatment codes and details of the two field experiments, Coimbatore.

Code	Details
Experiment 1	
DN	- no drainage, no special provision for increasing percolation and lateral movement of standing water
DW	- with drainage, providing an open drainage system around the plot to a width and depth of 60 cm for increasing percolation and lateral movement of standing water (assumption: impeded water table would be at least 60 cm below from the standing water)
H0	- No nitrogen at heading
HN	- 30 kg N ha^{-1} at heading as prilled urea.
Experiment 2	
Ic	- maintaining five cm water column in the field throughout the growth period, without exposing the oxidized layer of the ploughed soil to the open atmosphere (a condition in many of the farmers' holdings in the deltaic clay soils with a slope of land less than 1.0%, which normally leads to un-drained soil situation).
Id	- maintaining continuous standing water as in Ic up to panicle initiation then irrigating the field one day after the disappearance of ponded water.
N120	- 120 kg N ha^{-1} (50% basal, 25% each at 20 and 40 DAT)
N150	- 150 kg N ha^{-1} (50% basal, 25% each at 20 and 40 DAT)
N120HN	- 120 kg N ha^{-1} (50% basal, 25% each at 20 and 40 DAT) + 30 kg N at heading
N150HN	- 150 kg N ha^{-1} (50% basal, 25% each at 20 and 40 DAT) + 30 kg N at heading

In the EXPT2, four methods of water management were imposed, but only two of them are presented here (Table 1). In sub-plots, four levels of nitrogen were imposed. In all there were four main plots (water management) and four sub-plots (nitrogen management) This total of 16 subplots was arranged in split-plot design and was replicated three times. The soils of the experimental fields were moderately drained, deep and clay (40%) textured.

In EXPT1, root activity was monitored. Root length and volume were measured by scooping the roots along with soil and washing carefully in running water and then with distilled water. The roots were detached from the nodal bases. Any external moisture on the surface was removed by blotting paper and roots were weighed. Root volume was measured by volume displacement method. Roots were selected at random and their weight and length were recorded and related with the total root weight for obtaining total root length. Root activity, as the ability of the roots to oxidize α-naphthylamine, was measured by the procedure described by Ota (1970).

Nitrogen content of root, stem, leaves and panicles was estimated using the micro-Kjeldahl method (Humphries, 1956). The root cation exchange capacity was estimated using the method of Croche (1964).

Table 2. Details of the Experiment 1 and 2.

Particulars	EXPT1	EXPT2
Sowing	30.11.91	26.09.93
Transplanting	24.12.91	26.10.93
Variety	IR20	Pre-release culture
Depth of planting (cm)	2.5	2.5
Seedlings per hill (No.)	2	2
Spacing (cm)	20×10	20×10
Maximum tillering	25.01.92	25.11.93
Panicle initiation	21.02.92	03.12.93
Stray flowering	14.03.92	28.12.93
Heading (50% flowering)	21.03.92	03.01.94
Maturity	24.04.92	05.02.94

Results and discussion

Effect of drainage on root activity (EXPT1)

Provision of drainage (DW) resulted in significantly higher amount of root volume and total root length, from reproductive phase till maturity, compared to un-drained field situation (DN). In the un-drained field condition, root volume decreased after reaching a peak, by 38.2% of the peak value. This relative decrease was only 22.0% when there was drainage to the roots (Figure 1). Ramasamy et al. (1994) showed that higher root dry weights are associated with higher root volume and root length. Root volume and root length were not altered by N application after heading.

The root activity as measured by the α-NA oxidizing power decreased quickly as the age of the crop advanced from tillering to ripening in DN treatment. On the contrary, with the provision of drainage, the activities of the roots was not only higher, but also remained high until continued till ripening as it was seen (Figure 1). Dai (1988) related root oxidizing power with dry matter production. He predicted no further dry matter production when root oxidizing power dropped below 1.0 mg α-NA h^{-1} g^{-1} of root dry weight. The value under no-drainage system especially after heading was 2.1 mg h^{-1} g^{-1} of fresh root.

Further evidence of higher root activity under drainage system was seen by CEC of the roots. The CEC of the roots under DN conditions decreased gradually as the age advanced.

Jagadeesan & Rajamannar (1978) reported a CEC of 12.0 me/100 g of dry root at maturity. In the no-drainage plots, the CEC came down to 9.5 me/100 g at harvest from the initial level of 20.8 me/100 g (Figure 1).

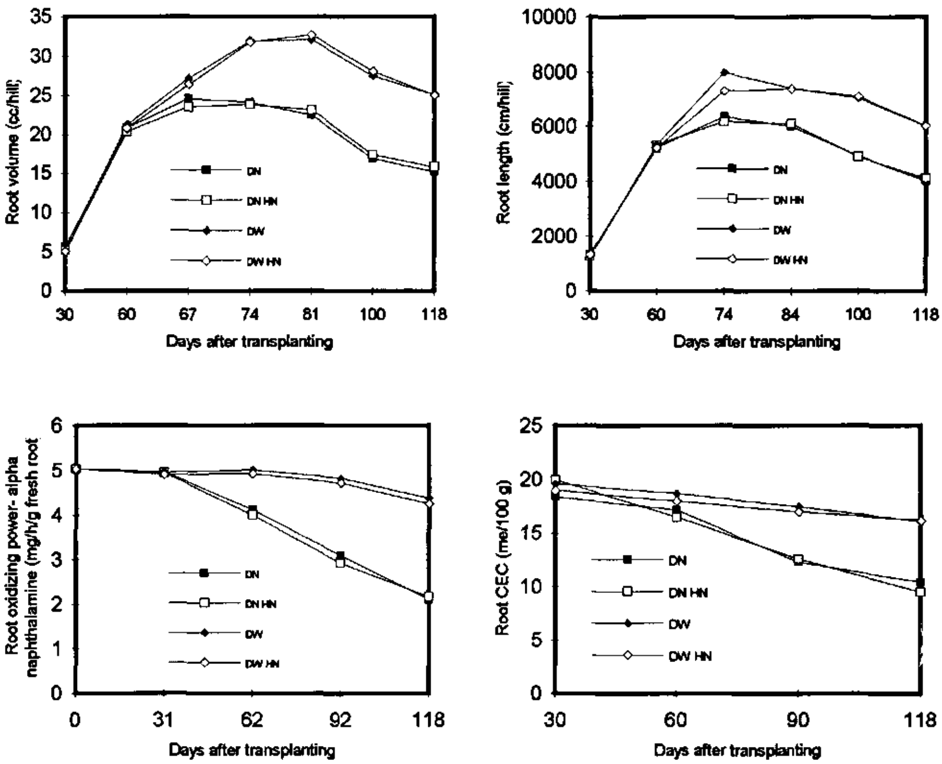

Figure 1. Effect of drainage and N application at heading on root characteristics of rice IR20, EXPT1 wet season 1991-92, Coimbatore. Treatment codes are explained in Table 1.

Yield attributes as affected by drainage and N application at heading (EXPT1)

Both the number of ear bearing tillers and the number of spikelets per panicle were higher in the absence of field drainage (Figure 2). Nevertheless, field drainage resulted in the production of more filled spikelets compared to un-drained plots. Top dressed N at heading stage caused further increase in the number of filled spikelets under drainage situation, while top dressing at heading has a reverse effect in the absence of drainage. Higher final grain yield was recorded with drainage. N application at heading increased the grain yield in drained soils and reduced the grain yield in undrained soils.

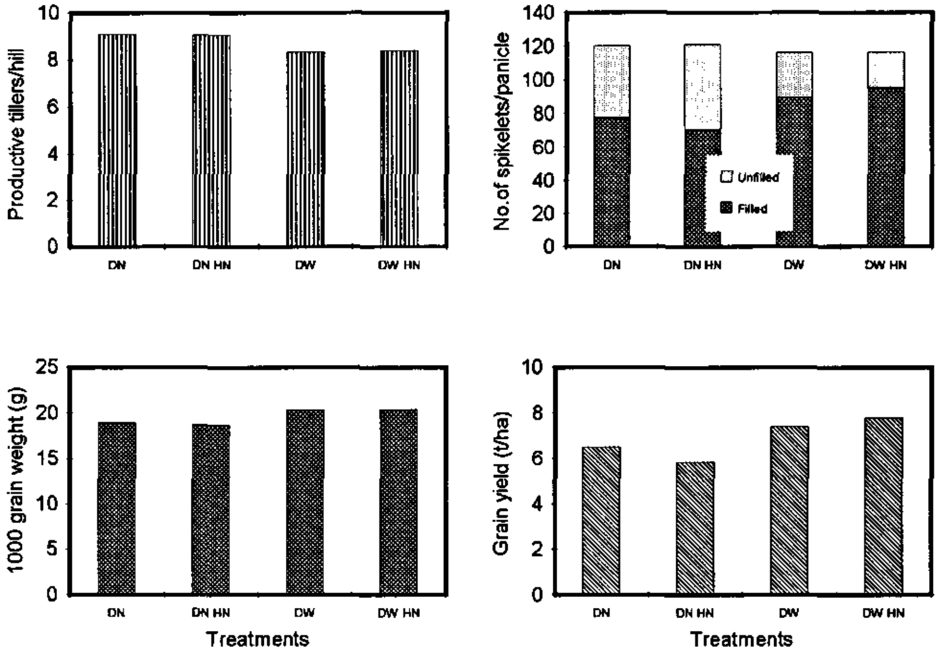

Figure 2. Yield and yield attributes as affected by drainage and N application at heading in rice IR20, WS, Coimbatore. Treatment codes are explained in Table 1.

Effects of irrigation management on crop growth (EXPT2)

Nitrogen concentration and uptake

Leaf and stem N concentrations decreased rapidly with crop, while root N concentration dropped only slightly (Table 3). Root N concentrations were relatively high in all treatments. The treatments induced only small variations in the N concentration of plant organs. Only root N content at heading and at maturity was strongly affected by water management. It was higher in Id, where irrigation was delayed one day after disappearance of the ponded water. In general, total N accumulation in leaf and stem increased up to heading and thereafter decreased. Nitrogen remobilization from leaf and stem ranged to a maximum of 20.5% only.

The total N uptake in the crop increased till maturity. Irrigating one day after disappearance of ponded water resulted in higher N uptake than continuous submergence. Uptake in the two N levels i.e., 120 and 150 kg N differed significantly, only under the former method of irrigation (Figure 3). Top-dressing of 30 kg N at heading was found to enhance the total N uptake only under drained condition. In general, the N uptake rate slowed down after heading (<0.5 kg ha^{-1} d^{-1}). Additional N received at heading resulted in increased rate of uptake, up to 0.9 kg ha^{-1} d^{-1} (Figure 4). The N recovery from 30 kg N

Table 3. Nitrogen content (%) in various plant organs at different stages, EXPT2, wet season, 1993-94.

Treatment	Panicle initiation (38 DAT)			Heading (69 DAT)			Maturity (102 DAT)		
	Leaf	Stem	Root	Leaf	Stem	Root	Straw	Root	Panicle
Ic N120	3.15	1.68	1.36	1.92	1.28	1.21	1.12	1.12	1.34
Ic N120 HN	3.12	1.70	1.30	1.94	1.28	1.20	1.14	1.16	1.34
Ic N150	3.26	1.74	1.34	1.98	1.30	1.24	1.12	1.10	1.36
Ic N150 HN	3.26	1.72	1.34	2.00	1.32	1.34	1.13	1.08	1.36
Mean	3.19	1.71	1.34	1.96	1.29	1.25	1.13	1.11	1.35
Id N120	3.16	1.70	1.32	1.92	1.30	1.32	1.12	1.24	1.34
Id N120 HN	3.14	1.66	1.36	1.94	1.28	1.30	1.14	1.26	1.36
Id H150	3.32	1.74	1.34	2.00	1.34	1.34	1.10	1.26	1.36
Id H150 HN	3.28	1.76	1.34	1.96	1.36	1.34	1.12	1.28	1.36
Mean	3.22	1.72	1.34	1.96	1.32	1.32	1.12	1.26	1.36

Ic - continuos standing water; Id - irrigation one day after disappearance of ponded water

N120,150 - N kg ha^{-1}; HN - 30 kg N applied at the time of heading

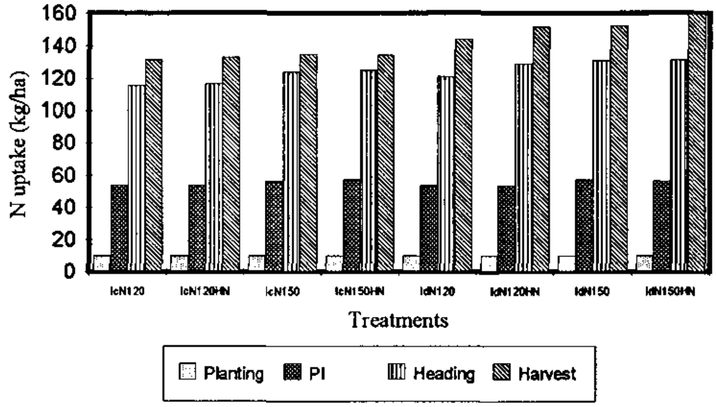

Figure 3. Effects of methods of irrigation and N application on total N uptake. EXPT2, wet season 1993-94, Coimbatore, India. Treatment codes are explained in Table 1.

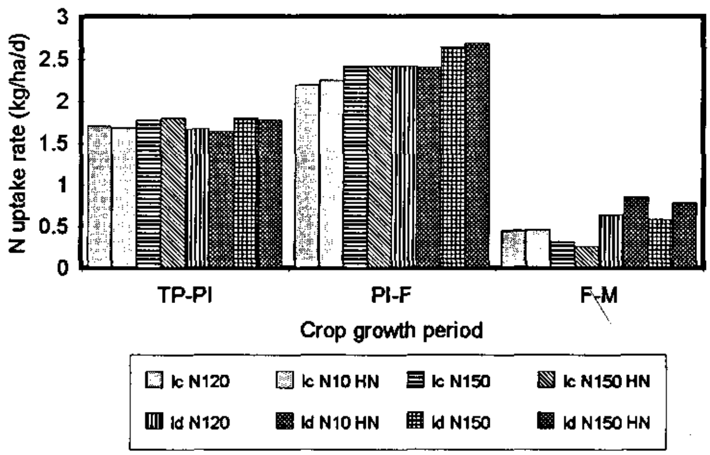

Figure 4. Effects of methods of irrigation and N application on N uptake rate. Treatment codes are explained in Table 1.

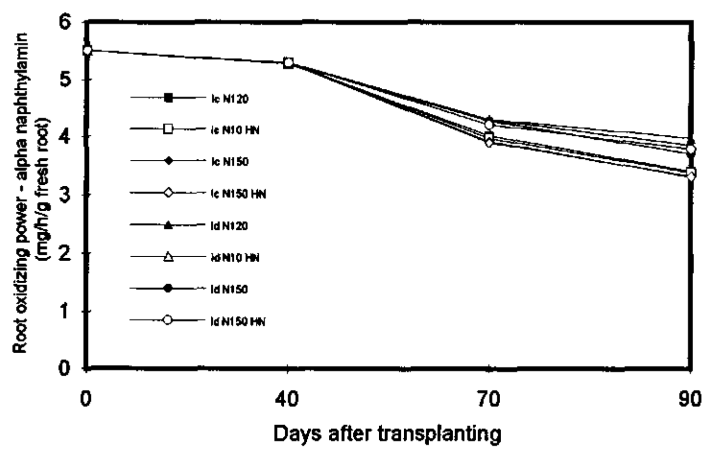

Figure 5. Effect of method of irrigation and N application on root oxidizing power. Treatment codes are explained in Table 1.

applied at heading ranged from 0.0 (IcN150) to 7.7/33 kg (IdN120). The higher N uptake rate and total N uptake may be due to prolonged root activity, a phenomenon noted in EXPT1. Indeed, root oxidizing power was enhanced, also in EXPT2, by drainage, as shown in Figure 5.

The concentration of N in the flag leaf was falling sharply after emergence. The N top-dressed at heading slowed down this decline for about two weeks after N application. Higher root activity was associated with flag leaf N in the initial periods (Figure 6).
Nitrogen concentration of the panicle also showed a declining trend from the day of panicle emergence, and attained a static level a week before full maturity of the panicle (Figure 6). Panicle weight increased from emergence till maturity. Again, there was a clear association with root activity. The slope of the curve had an upward shift due to N application at heading (Figure 7).

Yield and yield attributes (EXPT2)
Tiller production was not affected by irrigation methods but was affected by nitrogen application. The number of filled spikelets varied significantly. As observed in EXPT1, panicle weight as well as filled spikelets per unit area (m^2) were reduced also in EXPT2 by continuous submergence (Ic), this would be the equivalent of the no-drain situation in EXPT1. Here also, N top dressed at heading was found useful to improve the grain filling process under drained conditions only (Table 4).

Table 4. Effects of irrigation methods & N levels on a medium duration rice culture in WS, 1993-94, Coimbatore, India.

Treatments	Filled spikelets No. m^{-2}	Total biomass t ha^{-1}	Grain yield t ha^{-1}	Harvest Index
Ic N120	21,225	10.9	3.93	0.393
Ic N120 HN	21,654	11.0	3.98	0.362
Ic N150	21,526	11.2	3.85	0.345
Ic N150 HN	21,692	11.1	3.75	0.338
Mean	21,532	11.0	3.88	0.353
Id N120	23,121	10.8	4.46	0.413
Id N120 HN	28,836	12.7	5.08	0.400
Id N150	27,225	12.5	4.69	0.375
Id N150 HN	28,710	13.0	4.98	0.383
Mean	26,971	12.2	4.80	0.393

Ic - continuous standing water; Id - irrigation one day after disappearance of ponded water
N120,150 - N kg ha^{-1}; HN - 30 kg N applied at the time of heading

There were distinct variations in the grain yield due to irrigation methods followed. Irrigating the field one day after disappearance of ponded water (Id) especially after PI stage was found to increase the grain yield by 23% compared to continuous flooding. The higher grain yield in Id is explained by the improved filling of spikelets. This may be due to continued root activity. Ramasamy et al. (1994) reported better grain filling process and ultimately the grain yield due to prolonged root activity with better drainage system to roots. They also found that the better grain yield was due to thorough redistribution of stored reserves from the growing organs especially from stem. Mohammed et al. (1974) observed that nitrogen distribution in the rice plants were mainly by the conversion of ammonium and a part of nitrate nitrogen into organic nitrogen, mainly amides and amino acids in roots. Thus, roots are more vital for better grain yield, if not to transmit new nitrogen ions from soils to plant but for better redistribution of already stored reserves.

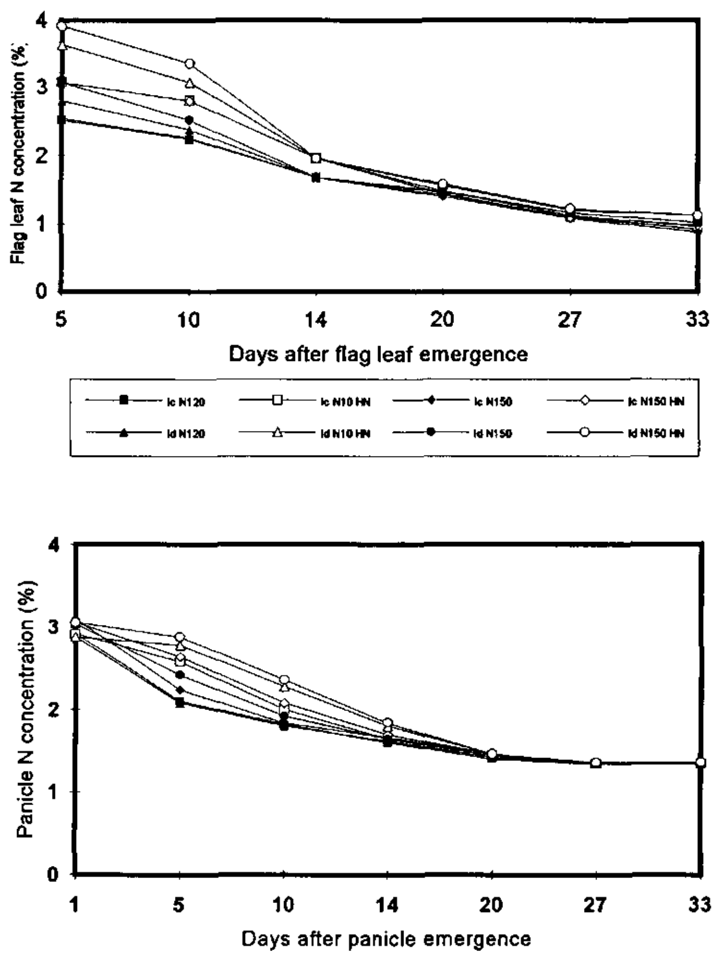

Figure 6. Effect of methods of irrigation and N application on N concentration in flag leaves and panicles after emergence. EXPT2, 1993-94, Coimbatore, India. Treatment codes are explained in Table 1.

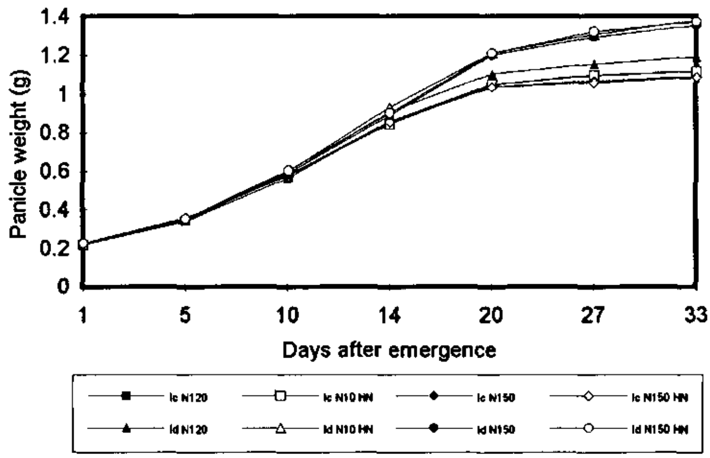

Figure 7. Effect of methods of irrigation and N application on the panicle weight after emergence. Treatment codes are explained in Table 1.

Additional N of 30 kg ha^{-1} top dressed as prilled urea, at the time of heading, with Id system of irrigation was found to increase the filled grains per unit area and grain yield by 14%. Positive response to N at heading was also reported by many workers (Pande & Singh, 1970; Wagh & Throat, 1988). The result was not positive for the same dose when it was given to a crop where the roots were inactive (Ic) by pulling down the filling process. Patel (1982) and Prasad & Rao (1987) cautioned not to go for N application beyond PI stage.

Conclusions

Provision of drainage to improve the percolation of standing water in a heavy clay soil (EXPT1) was found to prolong the root activity, root biomass, root volume, root length etc. Irrigating the field a day after the disappearance of ponded water from panicle initiation stage onward (EXPT2) also resulted in higher root activity. Improved/prolonged root activity might have been responsible for better distribution and redistribution of stem reserves to productive organs which improved the percentage of filled grains and grain yield. Top dressing of an additional N dose was effective to increase grain filling and grain yield only in a crop which had better root activity at heading stage. The reverse effect was observed under poor drainage (EXPT1) and continuously flooded (EXPT2) condition.

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Effects of N uptake on the sink and source of Indica-Japonica F1 hybrid

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Introduction

In recent years, great progress has been made in the breeding of the Indica-Japonica F1 hybrid, after the finding of the photoperiod-sensitive and thermo-sensitive genetic male-sterile line and varieties with wide compatibility. It has become possible to utilize the heterosis of Indica-Japonica F1 hybrid. Although there is evident yield potential in the present combinations, the low percentage of filled grains is a widespread problem limiting higher yields (Yun, 1990; Zhu, 1990). Until now the mechanism of the yield formation as been investigated in the aspects of dry matter production, nutrient absorption, sink and source and the characteristics of vascular bundles by Hong (1992), Lu (1992), Huang (1993), Shi (1993) and Xiao (1993). The imbalance in sink and source was thought to be the main cause of the low percentage of filled grains in the Indica-Japonica F1 hybrid (Lu, 1992; Huang, 1993). In order to accelerate the spreading process of Indica-Japonica F1 hybrid in farm fields, it is necessary first to solve the problem of the low percentage of the filled grains. In this paper, we discuss the relationship between N uptake and the formation of sink and source, and the effects of N application and planting density on the ratio sink/source ratio.

Materials and methods

A field experiment was conducted and two combinations were evaluated: one was the Indica-Japonica F1 hybrid, Ganhua7 (124-129 d) (5460s × Guang Keng Gen 2), another was the three-line F1 hybrid (check variety), Sanyou63 (131-136 d), which is one of the best varieties in Jiangxi province.

The experimental plot was a clay loam soil containing 3.29% organic matter, 0.12% total N, 81.0 ppm available N, 41.3 ppm available P, 54.1 ppm available K. The pH was 6.0. Potassium was applied at 112.5 kg ha^{-1} in the form of potassium chloride at 7 DAT. Phosphorous was applied at 63.8 kg ha^{-1} in the form of fused calcium-magnesium phosphate as basal dressing. Nitrogen application rates and planting densities are shown in Table 1. N was applied in the form of urea; 30% at 7 DAT and 70% at 21 DAT. Each treatment was replicated three times and the plot size was 3.4 x 4.0 m.

Eds T.M. Thiyagarajan, H.F.M. ten Berge & M.C.S. Wopereis. Nitrogen management studies in irrigated rice. 55
SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen and IRRI, Los Baños (1995), pp 55-64.

Table 1. Overview of N application and planting spacing.

Treatment	Combinations	N application ($kg\ ha^{-1}$)	Spacing (cm)
T1	Sanyou 63	150	13.3 × 18.3
T2	Sanyou 63	225	13.3 × 18.3
T3	Sanyou 63	0	16.7 × 20.0
T4	Sanyou 63	150	16.7 × 20.0
T5	Sanyou 63	225	16.7 × 20.0
T6	Ganhua 7	150	13.3 × 18.3
T7	Ganhua 7	225	13.3 × 18.3
T8	Ganhua 7	0	16.7 × 20.0
T9	Ganhua 7	150	16.7 × 20.0
T10	Ganhua 7	225	16.7 × 20.0
T11*	Sanyou 63	150+15	16.7 × 20.0
T12*	Ganhua 7	150+15	16.7 × 20.0

* additional 15 $kg\ ha^{-1}$ N was applied at heading.

Table 2. Effects of N uptake on sink and source at heading. Treatment details are furnished in Table 1.

Treatment	N uptake at heading (g/m^2)	Dry wt at heading (g/m^2)*	Panicle wt. at heading (g/m^2)*	Spikelet number ($10^4/m^2$)*	Sink capacity (g/m^2)*[a]	LAI at heading	Leaf wt. at heading (g/m^2)	Leaf wt.(mg)/ leaf area
T1	12.88	1009	149	3.81	1135	6.83	247.9	3.63
T2	15.72	1159	174	3.90	1139	8.91	304.4	3.42
T3	6.20	783	102	2.12	634	3.78	145.3	3.84
T4	10.88	895	121	3.02	891	6.13	218.9	3.57
T5	12.33	956	143	3.08	890	6.80	251.1	3.69
T6	12.35	936	176	5.06	1295	5.85	262.1	4.48
T7	17.17	1075	184	5.84	1483	6.88	290.7	4.23
T8	6.04	735	107	2.58	648	2.97	131.9	4.44
T9	11.92	870	150	4.43	1103	4.62	208.0	4.50
T10	12.59	906	153	5.09	1201	5.15	220.3	4.15

* The difference between two cultivars is significant at 5% level.

[a] Sink capacity: spikelet number × 1000 grain weight

Plant samples were taken from 5 hills for each treatment at each sampling time. Leaf area and dry weight were measured. The N content of plants was analysed by the Kjeldahl method. The unfilled grains were removed by water with a specific gravity of

1.0. The translocation from the stem and sheath was calculated by the difference in weight between heading and harvest.

At 10 % heading stage, panicles heading on the same day with uniform growth were chosen. The top branches were cut to investigate the effects of sink reduction on the percentage of filled grains of the bottom branch. Four treatments (check, 25%, 50% and 75% cutting of top branch) were imposed on twenty panicles selected for each treatment.

An additional 15 kg ha^{-1} of N was applied in the treatment of 150 kg ha^{-1} of N at the stage of 10% heading (T11, T12). Then the panicles heading on the same day with uniform growth were chosen, and marked. Then eight panicles with marks were sampled for weighing every five days. The effects of N application at heading on the dry matter production after heading was investigated.

Results and discussion

Effects of N uptake before heading on the formation of sink and source

Formation of sink

The amount of N uptake at heading increased with increased N application in all the treatments (Table 2). At the same N level, the amount of N uptake was also greater at higher planting density. The amount of N uptake by the Indica-Japonica F1 hybrid was much higher than by Sanyou63 at the higher N application level and higher planting density (T7). The plant weight, panicle weight, spikelet number and sink capacity (spikelet number x grain weight) were much affected by the level of N application. There was a close correlation between N uptake and plant weight, panicle weight, spikelet number and sink capacity (Figure 1). The plant weight of Ganhua7 was lower than that of Sanyou63 at heading, but the panicle weight, spikelet number and sink capacity of Ganhua7 were higher than Sanyou63.

Formation of source

The leaf area and leaf weight of both combinations at heading stage increased with increased N application and higher planting density. There was a close correlation between N uptake and leaf area and leaf weight (Figure 1). The leaf area of Ganhua7 was less than that of Sanyou63, but the difference of leaf weight between two combinations was small, which was due to the higher leaf weight per unit leaf area in Ganhua7 (Table 2).

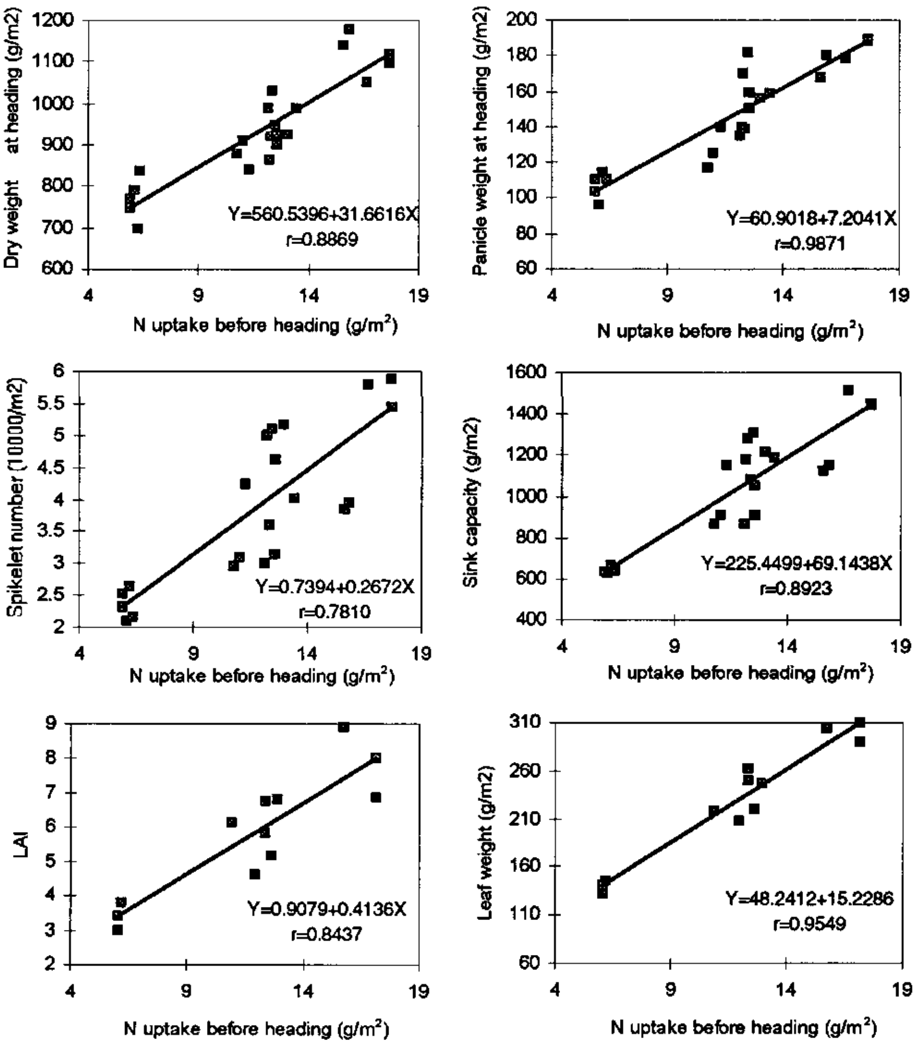


Figure 1. Effects of N uptake before heading on dry weight at heading, panicle weight at heading, spikelet number, sink capacity, LAI at heading and leaf weight at heading.

Effects of N uptake after heading on the source production

The N uptake after heading was higher at the higher planting density than at the lower planting density (Table 3). The amount of N uptake increased with the increased N application at the lower planting density. But at the higher planting density the amount of N uptake at 225 kg ha^{-1} of applied N was lower than that at 150 kg ha^{-1} applied N. There was a close correlation between dry matter production after heading and N uptake (Figure 2). Nitrogen uptake and dry matter production after heading were higher in Ganhua7 than in Sanyou63 at the same N level and the same plant density. But the translocation from stem and sheath to grain was less in Ganhua7 than in Sanyou63. Previous research (Shi, 1988) also indicated that plants with high N content show less translocation. More research is needed to find how to increase the increase the translocation from stems in plants with high N contents. High translocation at high N level can increase the fertilizer N efficiency.

Table 3. Effects of N uptake on the dry matter production after heading. Treatment details are given in Table 1.

Treatment	N uptake after heading ($g\ m^{-2}$)	Dry matter production after heading ($g\ m^{-2}$)*	Translocation amount from stem and sheath to panicle ($g\ m^{-2}$)*
T1	5.30	572	160.2
T2	3.53	569	114.6
T3	0.69	186	216.6
T4	2.55	520	140.4
T5	2.86	443	169.0
T6	6.59	725	3.0
T7	4.62	744	42.5
T8	1.13	233	137.9
T9	2.07	583	19.2
T10	3.20	632	19.0

* The difference between two cultivars is significant at 5% level.

Table 4. Ratio of sink /source at different N level and plant density. Treatment details are given in Table 1.

Treatment	Spikelet no./ leaf area(cm^2)*	Filled spikelet wt.(mg)/ leaf wt.(mg)	Sink capacity(mg)/ leaf wt. (mg)*
T1	0.56	3.42	4.47
T2	0.44	2.67	3.80
T3	0.56	3.48	4.49
T4	0.49	3.26	4.13
T5	0.45	3.29	3.47
T6	0.86	3.19	4.86
T7	0.85	3.12	5.08
T8	0.87	3.12	5.02
T9	0.96	3.38	5.23
T10	1.03	3.36	5.43

* The difference between two cultivars is significant at 5% level.

Regulation of N uptake on the ratio of sink/source

Regulation of N application and planting density on the ratio of sink/source

The ratio of sink/source is shown in Table 4, with leaf area and leaf weight as the index of source and total spikelet number, filled grain weight and sink capacity as the index of sink. Since there were large differences in 1000 grain weight (Table 5) and unit leaf weight (Table 2) between the two combinations, it was reasonable to use sink capacity as the potential sink and leaf weight as the source. Sink capacity includes the factors of spikelet number and grain weight, and leaf weight includes the factors of leaf area and leaf thickness. Previously, for the definition of the sink and source, the spikelet number per unit area (Wada, 1986; Lin, 1986) and sink capacity (Hong, 1992; Shi, 1993) were used as the index of sink. Leaf area was usually used as the index of source. Lin (1986) used the ratio of grain number/leaf area as an index to measure if the sink and source of rice population was suitable. Here the ratio of sink capacity/leaf weight is suggested as a better index for measuring the rice population than the ratio of grain number/leaf area, and it could also be widely suited to the different types of varieties.

Although there was large differences in the ratio of spikelet no./leaf area (almost double) between the two combinations, the difference in the weight of the filled grains borne per unit leaf weight was quite small in two combinations (Table 4). The effect of increased N uptake on the sink promotion was greater in Ganhua7, and its ratio of sink/source increased with increased N application. But the effect of N uptake on the source was greater in Sanyou63, where almost no increase of the sink capacity occurred as a result of increased N application at 150 kg ha^{-1} N level (Table 2). Hence, the ratio of sink/source decreased with increased N application. This meant that the formation of sink in Ganhua7 was more sensitive to N application. On the other hand, the formation of source in Sanyou63 was much affected by N application. It is worth to notice that the ratio of sink/source in Ganhua7 was lower at the higher planting density, but it was higher in Sanyou 63. Therefore, it is possible that the ratio of sink/source of Indica-Japonica F1 hybrids could be improved at certain level by adjusting planting density and N management.

Effects of N application at heading on dry matter production

Application of 15 kg ha^{-1} of N at 10% heading stage enhanced the N content of leaf by 9.3 and 11.5% for Ganhua7 and Sanyou63, respectively. There were no significant differences in dry matter production between the treatments with and without N application at heading. This indicated that N application at heading did not increase dry matter production after heading at a preflowering N application rate of 150 kg ha^{-1} which is contrary to the results of previous research (Li, 1993). The different effects of N application at heading on dry matter production may be caused by the rate of N application before heading. Above a certain level of N application, the net photosynthesis of leaves might not increase further with the increase of the N content of leaf.

Effects of N uptake on yield and yield components

Total N uptake increased with increased N application and planting density (Table 5). Nitrogen uptake in Ganhua7 was higher than that in Sanyou63, There was a close correlation between N uptake and grain yield (Figure 2). The panicle number in both combinations increased with the increased N application and planting density. Ganhua7 had lower panicle number but more spikelets per panicle than Sanyou63. The spikelet number per panicle could be reduced by the increase of the planting density in Ganhua7. Grain weight decreased with increased N application in both combinations. Grain weight of Ganhua7 was lower than that of Sanyou63. The low percentage of the filled grains in Ganhua7 was related to its higher ratio of sink/source. Previous research also indicated that Ganhua7 belongs to the type of source limited and Sanyou63 belongs to the type of sink limited (Huang, 1993). The results of sink reduction by cutting of top panicle branches showed that the filled grain percentage could be enhanced in Ganhua7 (Table 6). The filled grain percentage at the bottom branches was also very high if the source was sufficient, which indicated that there was no great effect of "flow" and other factors on the filled grain percentage, as reported by Lu (1992) and Huang (1993).

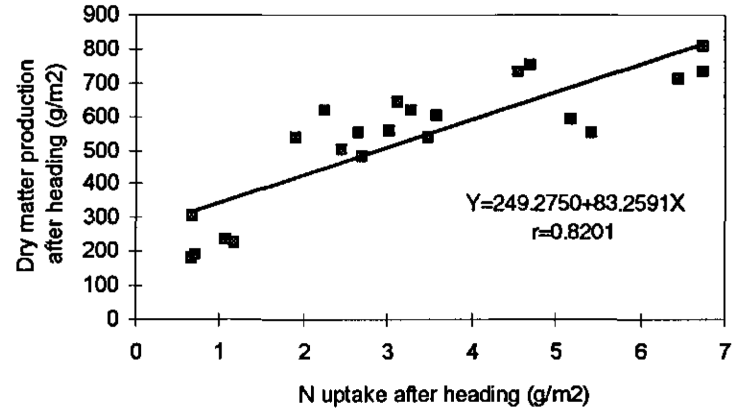
Table 5. Effects of N uptake on yield and yield components.

Treatment	Total N uptake (kg ha^{-1})*	Panicle number (m^2)*	Spikelet number/ panicle*	Filled grains (%)*	1000 grain weight (g)*	Grain yield (kg ha^{-1})
T1	181.7	302	126.1	81.0	29.8	8474
T2	192.5	328	118.9	73.3	29.2	8118
T3	68.9	193	110.0	79.4	29.9	5057
T4	134.3	251	120.4	83.9	29.5	7130
T5	151.9	259	118.9	81.1	28.9	7155
T6	189.3	279	180.9	71.5	25.6	8368
T7	217.9	319	182.8	71.8	25.4	9073
T8	71.7	167	154.7	70.1	25.1	4120
T9	139.9	222	199.1	64.9	24.9	7035
T10	157.9	250	203.7	61.5	23.6	7141

* The difference between two cultivars is significant at 5% level.

Table 6. Effects of the top branch cutting on the filled grains percentage in Ganhua7.

Position	Check branches cutting	Three top branches cutting	Six top branches cutting	Nine top
Top three branches (1-3)	86.50%			
Middle three branches (4-6)	77.80%	88.30%		
Remaining branches	60.60%	64.70%	88.10%	87.20%



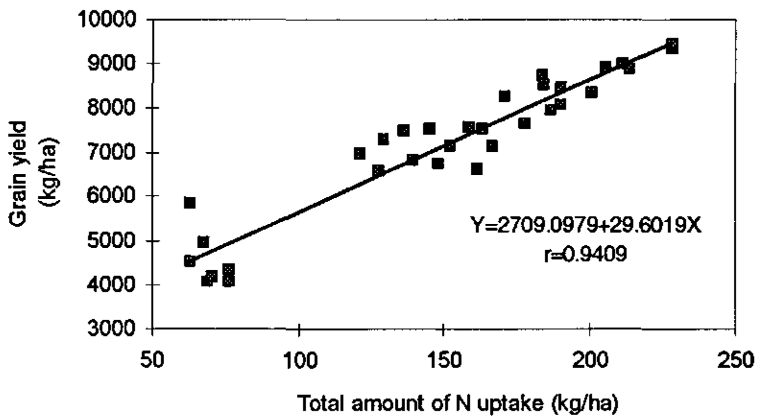


Figure 2. Effect of N uptake after heading on dry matter production after heading and grain yield.

Conclusions

There was a close correlation between N uptake and the formation of sink and source. The sink capacity as defined by spikelet number per $m^2 \times 1000$ grain weight and leaf weight are suggested as indices of sink and source, respectively. The low percentage of filled grain in Ganhua7 was mainly due to its high ratio of sink/source. The sink formation of the Indica-Japonica F1 hybrid Ganhua7 was more sensitive to N application than its source size. The ratio of sink/source increased with increased N application in Ganhua7, but decreased at higher planting density. Therefore, it is possible that the ratio of sink/source of Indica-Japonica F1 hybrids could be improved at certain level by adjusting planting density and N management.

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* In Chinese with English summary.

Effect of timing and amount of N application on the nitrogen recovery and plant growth

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Introduction

Rice production has increased over the past decades and approximately 60% of the raise in production is attributed to more intensive cultivation. Of this increase, 62% is attributed to the increased use of fertilizer (Vlek & Byrenes, 1986). Nitrogen (N) is the most important among the applied fertilizer nutrients. Dry mass and grain yield are usually related closely with N uptake. The uptake and loss of applied fertilizer-N has been studied intensively in different countries in recent years (Craswell, 1979; De Datta & Patrick, 1986; Wopereis et al., 1994; Thiyagarajan et al., 1994). Responses to applied N are highly variable depending on soil type, amount and timing of fertilizer-N application and other practices.

A model, ORYZA-0, was developed (ten Berge et al., 1994b) for optimizing the timing and amount of N application in order to increase the rice production and decrease the loss of applied fertilizer-N. To use this model, it is necessary to quantify the supply of soil-N, N uptake limitations by the plant at different times, and the potential fertilizer-N recovery rate. The ensuing recommendations generated by the model are strongly affected by these coefficients.

This paper reports a field experiment conducted to determine the potential recovery rate of fertilizer-N, applied at different times and in different amounts. The effects of N uptake on plant growth were also investigated.

Materials and methods

The experiment was conducted at Jiangxi Agricultural University, Nanchang, P.R.China in 1994 late season. The experiment plot was a clay loam soil containing 3.12% organic matter, 0.2% total N, 150.3 ppm available N, 21.3 ppm available P, 44.9 ppm available K. The pH was 5.5. A high-yielding three-line F1 hybrid, Sanyou63 was grown from 14 July (transplanting date) to 25 October (harvest date). The seedling age at transplanting was 30 days. Plant spacing was 13.3 x 20 cm. Nitrogen (in the form of urea) application time and

Table 1. Overview of timing and amount of N application (late season, 1994, Jiangxi cvar Sanyou63)

	N applied (kg ha $^{-1}$)						
Treatment	0 DAT	10 DAT	25 DAT	40 DAT	Heading	15 DAH	Total
T1	0	0	0	0	0	0	0
T2	50	0	0	0	0	0	50
T3	0	50	0	0	0	0	50
T4	0	0	50	0	0	0	50
T5	0	0	0	50	0	0	50
T6	0	0	0	0	50	0	50
T7	0	0	0	0	0	50	50
T8	0	100	0	0	0	0	100
T9	0	50	0	50	50	0	100
T10	50	50	0	50	50	0	150

amounts are presented in Table 1. Potassium was applied at 112.5 kg ha^{-1} in the form of potassium chloride at 10 days after transplanting (DAT). Phosphorous was applied at 63.8 kg ha^{-1} in the form of fused calcium-magnesium phosphate as basal dressing. The trial consisted of a randomized block with four replications and the size of each plot was 4.0 x 4.2 m. To prevent loss of N by runoff, the bund of each plot was covered by a plastic sheet.

Five hills were sampled in each plot just before every fertilizer application. At final sampling (one day before harvest) 10 hills were sampled, 5 hills for dry mass measurement and another 5 hills for yield component analysis. The plants were separated into roots, stems including leaf sheaths, green leaves, dead leaves and panicles. The plant height, dynamics of tillering, and the length of the top most fully-extended leaf were measured. After determination of dry mass, samples were ground and the N content of plant organs was analyzed by the Kjeldahl method.

Results and discussion

N recovery

The total amount of N uptake depended on the timing and amount of N application (Table 2). Recoveries as discussed in this study are apparent fertilizer N recoveries determined after correcting the total crop N uptake for the reference uptake, i.e. in unfertilized plots. At 50 kg ha^{-1} applied N level (T2 to T7), the N recovery was highest in T5 (N applied at 40 DAT), and amounted to 86% at 17 days after application and 97% at harvest (Table 3). Figure 1 shows the recovery evaluated at about 15 DAA (days after N application) and at

Table 2. Total N uptake (kg ha^{-1}), late season, 1994, Jiangxi, cvar Sanyou63.

	Treatments									
DAT	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
0	8	8	8	8	8	8	8	8	8	8
10	10	22	11	11	9	9	10	12	11	19
25	26	39	53	27	25	28	27	60	51	66
40	40	58	71	67	43	38	41	86	61	83
57	58	73	89	81	102	57	59	110	138	142
74	68	80	95	100	112	100	69	117	145	147
100	79	97	113	122	128	110	111	137	161	158

Table 3. N recovery (%), late season, 1994, Jiangxi, cvar Sanyou63.

	Treatments								
DAT	T2	T3	T4	T5	T6	T7	T8	T9	T10
10	24								18
25		55					34	50	53
40			53						
57				86				98	78
74					67				
100	35	67	86	97	61	63	57	82	52

harvest. The total N uptake from the plot of 100 kg ha^{-1} applied N was higher than that of 50 kg ha^{-1}, but the recovery was lower than that at 50 kg ha^{-1} applied N level. At 100 kg ha^{-1} applied N level, the uptake and recovery were much higher in T9 with two split applications (10 DAT and 40 DAT) than in T8 with one single application (10 DAT). In this experiment N application at 150 kg ha^{-1} (T10) did not increase the total N uptake if compared with T9 (100 kg ha^{-1}). Disease (rice blast occurred) and low radiation after heading may have been the main reasons for the relatively low N uptake in T10. A surprising phenomenon is the high recovery (63%) when N was applied 15 days after heading (T7). N recovery from a given split application increased further during the period from 15 DAA up to harvest (Figure 1). This may have had two causes: (1) application enhances extra root development and thereby increases uptake of native soil N; (2) uptake from the applied amount continues after 15 DAA. At 10 DAT N application, the recovery with pre-application (0 DAT in T10) was almost the same (Figure 2) as that without pre-application (T3). For application at 40 DAT, the recovery in T9 (with pre-application at 25 DAT) was even higher (98%) than in T5 (86%, without pre-application), but recovery in

T10 (78%, with pre-application at 25 DAT) was lower. This phenomenon confirms that the recovery rate was very high when N was applied at 40 DAT.

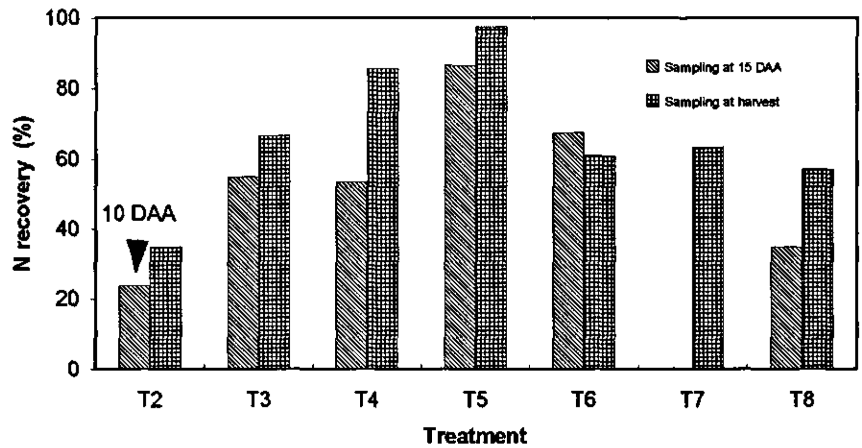

Figure 1. Recovery of applied N in the different treatments. Late season, 1994, Jiangxi, cvar Sanyou63. Treatment codes are explained in Table 1.

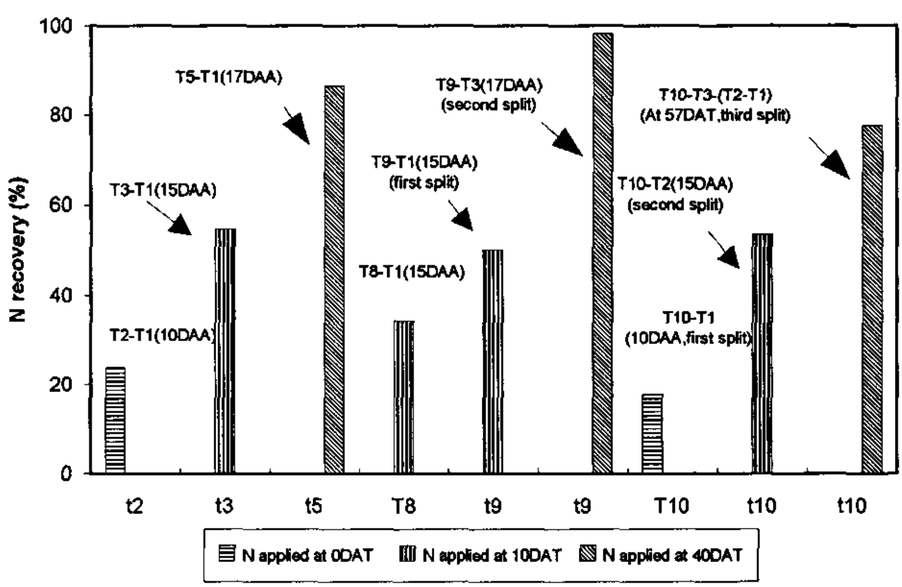

Figure 2. Comparison of N recovery with and without prior N application. Late season, 1994, Jiangxi. Treatment codes are explained in Table 1.

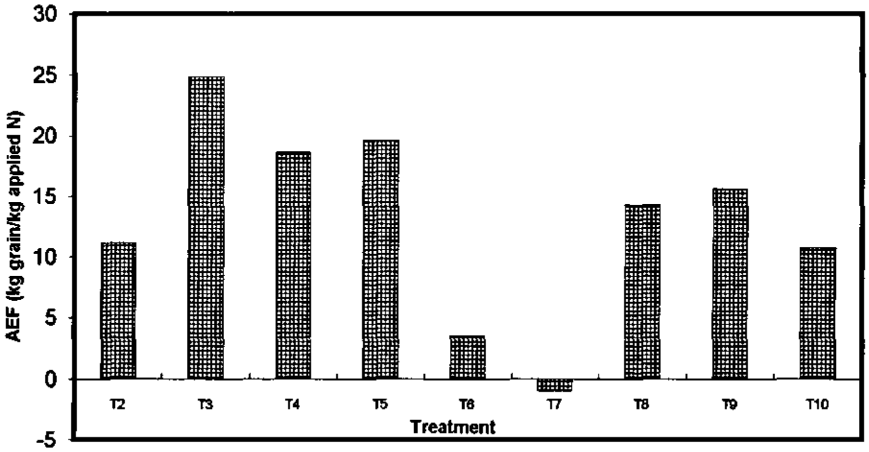

Figure 3. Agronomic efficiency (AEF) for the different treatments. Late season, 1994, Jiangxi. Treatments codes are explained in Table 1.

Previous reports indicate that the N recovery in the field was about 20-50% (Prasad & De Datta, 1979; Mitsui, 1954), and 37-67% (ten Berge et al., 1994a). Recovery in an ^{15}N experiment reported by Craswell & Vlek (1979) was in the range of 7-68%. N recovery was much affected by the timing and amount of N application in our experiment. Low amounts of N input, late application and the absence of runoff might have been the causes of the high N recoveries found in this experiment.

Agronomic efficiency (AEF)

High AEF (kg grain/kg applied N) did not always coincide with high N recovery, or *vice versa* (Figure 3). Among the 50 kg ha^{-1} N application level (T2 to T7), T3 had the highest AEF (about 25 kg grain/kg applied N), which touches the upper boundary of the range estimated by Yoshida (1981) (15-25 kg grain/kg applied N). Within the 50 kg ha^{-1} treatments the AEF was lower at later application of the fertilizer. This result agrees well with ORYZA-0 model recommendation. Although N application at 40 DAT (T5) gave the highest recovery , the reduced panicle number (Table 7), the high N content in plant organs (Table 4) and the delay in biomass accumulation probably led to reduced AEF. The roots' ability for N uptake was still very high after heading in this experiment (T6, T7), but the AEF of N applied at heading was very low; it was even below zero when N was applied at 15 DAH (days after heading).

Table 4. N content in plant organs at harvest (%), late season, 1994, Jiangxi, cvar Sanyou63.

Plant part	Treatment T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Root	0.61	0.66	0.69	0.65	0.73	0.63	0.60	0.78	0.73	0.77
Stem	0.43	0.45	0.46	0.55	0.74	0.55	0.55	0.62	0.78	0.63
Leaf	0.65	0.67	0.67	0.76	1.15	0.93	0.99	0.99	1.14	1.14
Panicle	1.01	1.01	1.01	1.10	1.22	1.27	1.26	1.14	1.39	1.36

Table 5. FSV values for the different treatments. Late season, 1994, Jiangxi, cvar Sanyou63.

Treatment	FSV1	FSV2
T1	1.04	0.20
T2	0.90	0.34
T3	0.93	0.56
T4	0.95	0.80
T5	1.08	0.51
T6	1.06	0.50
T7	1.04	0.46
T8	0.89	0.48
T9	0.96	0.42
T10	0.88	0.45

The slightly negative value of AEF found for application at 15 DAH may be due to measurement errors. The low AEF in T6 and T7 was associated with a small sink size (Table 7). The AEF decreased when the amount of N application increased. The same tendency was observed for total biomass (Table 5). Therefore, it is concluded that high N recoveries are not always accompanied with high grain yields. Wopereis et al. (1994) also found that the recovery was lower when N was applied before PI than for application after PI (up to flowering). In their case, however, AEF did not decrease under high N uptake and recovery and this could be due to a even distribution over time than in our case.

FSV

The crop growth rate (g m^{-2} d^{-1}) in the ORYZA-0 model is calculated from daily incident global radiation and the amount of N contained in the leaf canopy. We determined the value of the factor FSV (ten Berge et al., 1994c) which expresses the efficiency by which light and leaf nitrogen are used to produce crop biomass. This variable can be evaluated over the pre-flowering period (FSV1) and over the post-flowering period (FSV2). We used values of p = 10 g g^{-1} d^{-1} and ε = 2.5 g MJ^{-1} as suggested by ten Berge et al. (1994c). Table 5 shows that the FSV1 was in the range 0.9-1.1, which is considered high. FSV1 was found to be higher than FSV2 in all treatments. The FSV1 was higher in treatments where N was applied late (T5, T6, T7) than in the treatments with early application (T2, T3, T4) at 50 kg ha^{-1} of applied N level. The FSV1 in higher N application treatments (T8, T9, T10) was slightly lower than that of 50 kg ha^{-1}. FSV is apparently not only a site-variety interaction factor because its value changed slightly with the timing and amount of applied N. Further study should reveal which factors affect the value of FSV.

Dry mass

The total dry mass production was higher in all treatments which received N application than in the check, T1 (Table 6). At 50 kg ha^{-1} applied N, N application at 10 DAT (T3) and 25 DAT (T4) resulted in higher dry mass than earlier application (T2) and later application (T5, T6, T7). In T8, T9 and T10 there was higher N application but the dry mass was almost the same as in the T3 and T4, which is attributed to the low radiation after heading. The dry mass at heading was higher in T8, T9 and T10. There was a close correlation between the N uptake and dry mass (Figure 4). At sampling day 40 DAT the slope of dry mass vs. N uptake across all treatments was highest.

Tiller production

Figure 5 shows the dynamics of tiller production. Early application of N evidently increased the tiller number. The panicle number at harvest was equal to the tiller number at about 20 DAT, which suggests that increasing the tiller number before 20 DAT can increase the panicle number. Tillers produced after 20 DAT will have little or no contribution to the number of panicles. The date of 20 DAT is here called 'the termination date of effective tillering'. The termination date of effective tillering was reached earlier when N was applied

Table 6. Total biomass (kg ha^{-1}). Late season, 1994, Jiangxi, cvar Sanyou 63.

DAT	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
0	363	363	363	363	363	363	363	363	363	363
10	673	1011	737	675	573	579	693	739	721	901
25	1822	2745	3061	1891	1744	1984	1871	2833	2998	3374
40	3915	5705	6432	4755	3936	3697	3997	6123	5386	6832
59	7667	10071	10577	9239	8806	7592	7916	11187	10996	11413
74	9851	11205	11627	11728	9813	9813	9798	12768	12340	13323
100	10586	12533	14662	14240	12363	11517	11574	14645	14313	14807

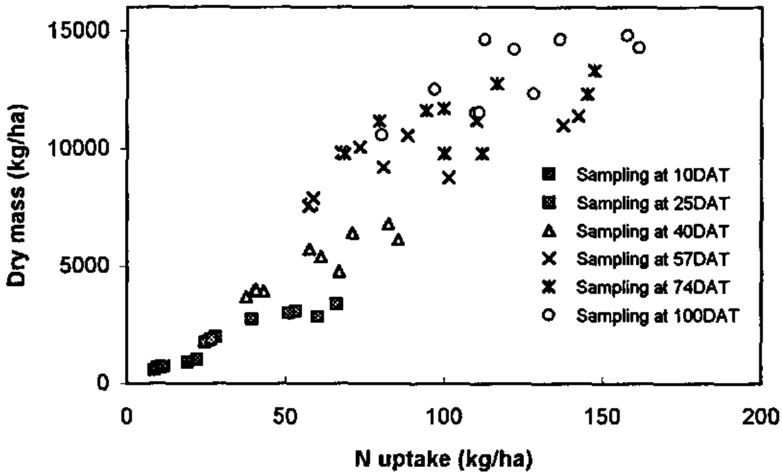

Figure 4. Relationship between the N uptake and dry mass at different growth stages. Late season, 1994, Jiangxi. cvar Sanyou63.

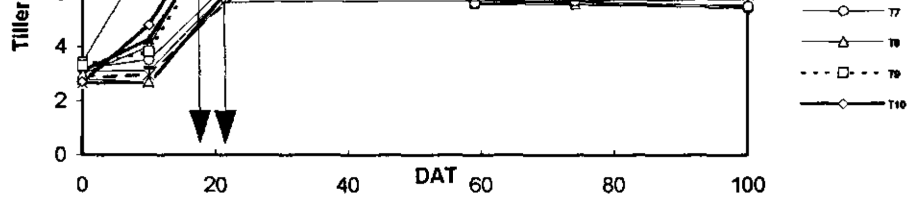

Figure 5. Tiller number as a function of days after transplanting (DAT). Treatment codes are explained in Table 1.

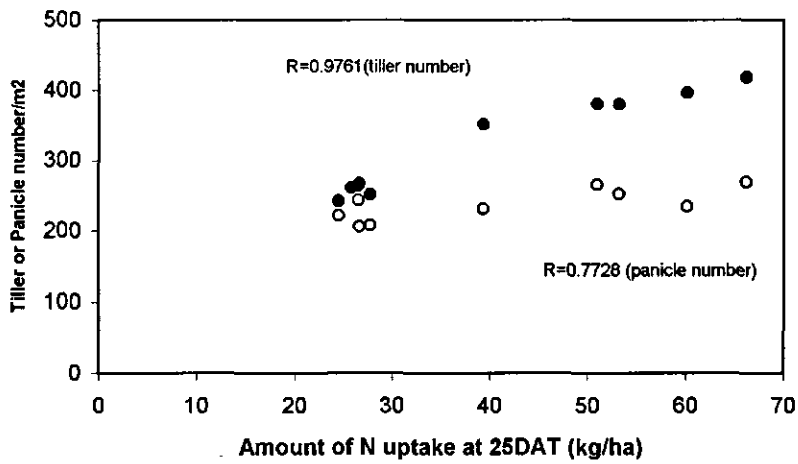

Figure 6. Relationship between N uptake and tiller number. Late season, 1994. Jiangxi, cvar Sanyou63.

at early stages. Figure 6 also indicates there was a close correlation between the N uptake at 25 DAT and the tiller number and panicle number. An application of 50 kg ha^{-1} N was already enough to produce a sufficient number of tillers, when N was applied at early stages. More N application is not necessary for the production of tillers. But if late N application (40 DAT) was there, the panicle number (T9) was increased. It even had the same number of tillers as T3 at 25 DAT (Figure 5). Late application reduced dying of tillers after 25 DAT, which shift 'the termination date of effective tillering' later. There was a close correlation between tiller number and dry mass at each of several growth stages. These results also confirm ORYZA-0 recommendation (ten Berge et al., 1994b) that N should be applied early for low total-N input conditions, because early N application increases the effective tiller number, and the dry mass is also proportional to the tiller number.

Spikelet formation

The spikelet number was different in the different N treatments (Table 7). There was a close correlation between the N uptake from PI to heading (25 to 57 DAT) and the number of spikelets per panicle (Figure 7). The number of spikelets per panicle in T5 was higher per m^2 was correlated with both (1) the N uptake from PI to heading and (2) the total N uptake at heading (Figure 8). As the total N uptake at heading includes two parts (a. the N than in the other treatments at the 50 kg ha^{-1} applied N level. Higher N application (T8, T9 and T10) did not increase the spikelet number per panicle further. The number of spikelets uptake before PI (25 DAT) which was correlated with tiller number; b. the N uptake from

PI to heading (57 DAT) which was correlated with spikelets per panicle), it could be used as an index of sink size in rice production. Instead of this index, biomass at heading could also be used, because it is highly correlated with N uptake. But when N uptake is above certain level the relation between N uptake and the spikelets per m^2 is not linear (Akita, 1987; Shi, 1993).

Table 7. Yield and yield components. Late season, 1994, Jiangxi, cvar Sanyou63.

Treatment	Panicles /m^2	Spikelets /panicle	Spikelets /m2*10^4	Filled grain(%)	1000 Grain wt.(g)	Grain yield* (kg/ha)	HI
T1	204	107	2.18	82.6	23.77	5051	0.42
T2	231	109	2.51	80.0	24.66	5686	0.40
T3	252	112	2.83	81.8	24.39	6469	0.39
T4	243	115	2.80	82.1	24.21	6113	0.38
T5	222	126	2.80	80.7	23.07	6169	0.44
T6	208	105	2.19	86.4	24.39	5250	0.40
T7	206	108	2.22	87.3	24.21	4996	0.38
T8	234	124	2.90	82.2	24.39	6684	0.40
T9	266	125	3.31	76.9	24.12	6831	0.42
T10	269	127	3.41	73.5	24.04	6884	0.41

* 14% moisture

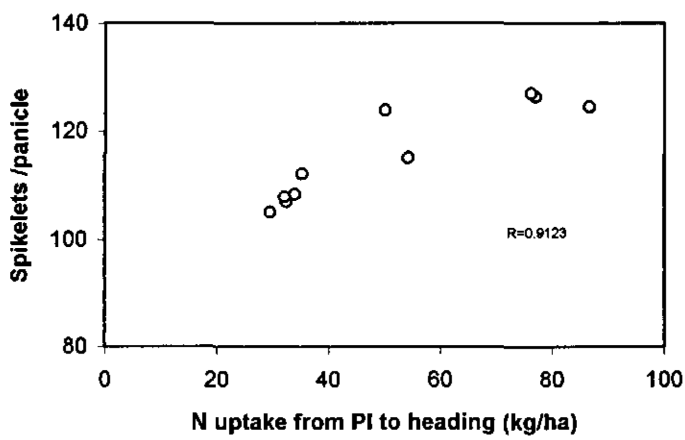

Figure 7. Relationship between N uptake from PI to heading and total uptake with spikelets per panicle.

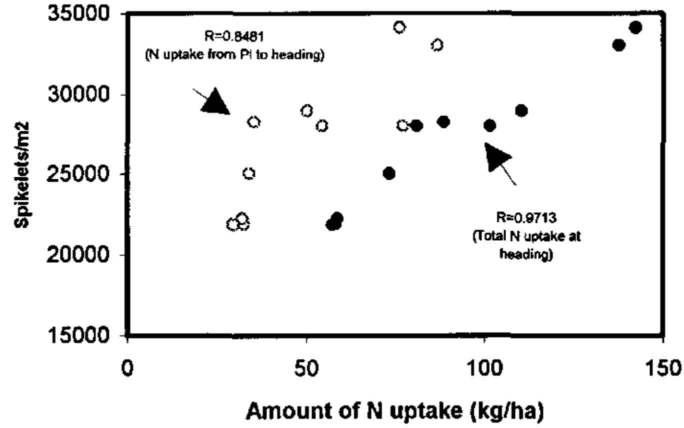

Figure 8. Relationship between N uptake and spikelets per m^{-2}. Late season, 1994, Jiangxi, cvar Sanyou63.

Leaf length and plant height

Leaf length was affected by the leaf N content at all stages except at 10 DAT (Figure 9). The slope of leaf length vs. leaf N content was steepest at 25 DAT. Plant height was also closely correlated with the N uptake from 10 DAT to heading (Figure 10). The plant height and tiller number seem to be good relative indices to rank treatments with respect to the N uptake amounts without damaging the rice plant. Therefore, it is worthy to do some, experiments with different plant types to confirm this hypothesis.

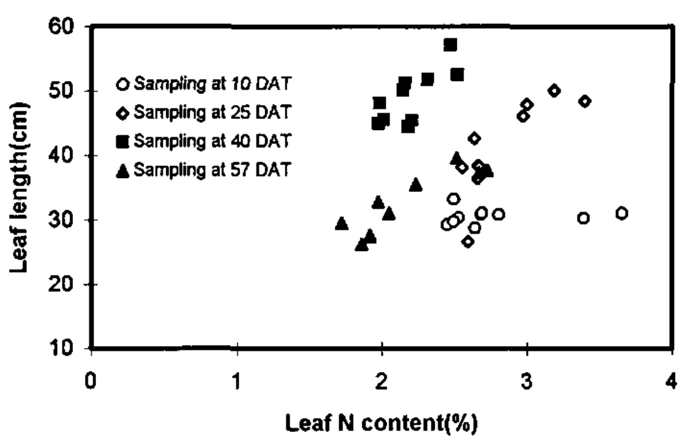

Figure 9. Relationship between leaf n content and leaf length. Late season 1994, Jiangxi, cvar Sanyou63.

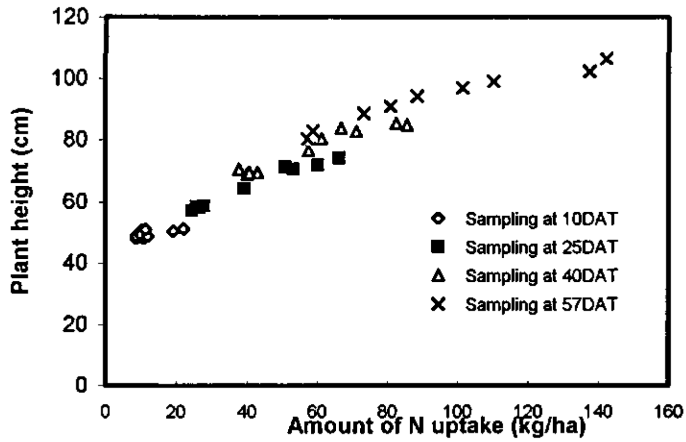

Figure 10. Relationship between N uptake and plant height at different growth stages. Late season 1994, Jiangxi, cvar Sanyou63.

Conclusions

The N recovery was highest (97%) for N application at 40 DAT, and was not much affected by prior application, at the present input levels of 50 kg/ha. The recovery of N in this experiment ranged from 35% to 97% as evaluated at harvest. The rice plant can still recover 61 - 63% of N applied at heading or at 15 days after heading. However, high N recovery are not always accompanied with high agronomic efficiency because of the relative small sink size in crops that suffered N shortage in early stages. The recovery of N applied in two splits was much higher than in one split at the same N level of 100 kg ha^{-1}. The agronomic efficiency at 50 kg level was highest when N was applied at 10 DAT, and was lower at higher amounts and at later applications. There was a close correlation between N uptake and dry mass at all stages. The final panicle number was equal to the tiller number at 20 DAT, which was also related with amount of N uptake. The number of spikelets per panicle was affected by the N uptake from PI to heading. There was a limitation to spikelet formation when N application was increased. Leaf length and plant height were also much affected by N uptake.

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Tillering pattern in rice *cvar* ADT38 under different nitrogen management practices

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Introduction

One of the yield determinants in rice is the number of tillers per unit area which can ultimately produce panicles. Although the tillering pattern in a transplanted crop depends upon factors like varietal characteristics, age of seedlings, depth of planting, water management, weed interference and other management and environmental factors, the role of nitrogen can be singled out for its significant effect (Matsushima, 1986; Thiyagarajan et al., 1993). Several studies (Thiyagarajan et al., 1993; Wopereis et al., 1993; Makarim et al., 1993) have shown that in specific situations higher grain yield could still be obtained even if the N application was delayed upto panicle initiation (PI). The present study was undertaken to observe the time course of tillering pattern in rice under different N management practices.

Materials and methods

A field experiment was conducted at Tamil Nadu Rice Research Institute (TNRRI), Aduthurai, India, in a replicated randomized design with four N management treatments. The details of experiments and treatments are presented in Tables 1 and 2.

Table 1. Details of the field experiment.

Season	: Sep. 1993 - Feb. 1994 (WS)
Variety	: ADT38 (135 days duration)
Planting density	: 50 per m^2
No. of seedlings per hill	: 1
Date of sowing	: 21 September 1993
Date of planting	: 25 October 1993
Date of panicle initiation	: 2 December 1993
Date of flowering	: 5 January 1994
Date of harvest	: 14 February 1994

Table 2. Treatment (N application) details.

Time of application	N source	N applied (kg ha^{-1})			
		T1	T2	T3	T4
7 DBT	Sesbania	0	0	55	75
0 DAT	Urea	0	30	30	0
10 DAT	Urea	0	30	30	0
23 DAT	Urea	0	30	30	15
38 DAT	Urea	0	30	30	50
51 DAT	Urea	0	0	0	15
66 DAT	Urea	0	30	30	20
	Total	0	150	205	175

DBT : Days before transplanting

DAT : Days after transplanting

In each plot (20 m^2) in a replication, two rows were selected and in each row 10 consecutive hills were selected. Tiller number was counted in the 20 selected hills for each plot on 10, 23, 38, 51 and 66 DAT and the productive tillers were counted at the time of harvest. The tiller number multi-observation data were analyzed for the variances of treatment and sampling error as well as the coefficient of variation (Gomez & Gomez, 1984). The grain yield was also recorded after the final harvest.

Results and discussions

The treatment effects on the number of tillers per hill were non-significant upto 23 DAT which justified the delaying of the urea-N application in T4 upto that stage. After that the control treatment (zero-N) had significantly lower number of tillers than the other treatments which in turn were equal (Table 3). The maximum number of tillers was reached at 51 DAT (13 days after PI) in all the treatments (Table 4). Hanada (1993) pointed out that the maximum-tiller-number stage could occur before or after or at PI stage depending upon the duration of the variety and concluded that the increase in tiller number is inhibited by the competition for nutrients between the tillers and the mother stem. The number of tillers per m^2 was highest in T2 at 23 DAT, in T3 at 38 and 51 DAT and in T4 at flowering and harvest (Figure 1). The tiller production rate (Figure 2) was highest in T2 upto 23 DAT indicating that urea-N supply is beneficial than green manure (T4) or its combination with urea-N (T3) in increasing the tiller number. Between 23 and 38 DAT (AT-PI), rate of tillering was higher in T3 exhibiting the combined effect of green manure and urea-N.

Application of urea-N at 38 DAT resulted in increased tiller number if green manure had been applied (T3 and T4) and in T2, there was no marked tillering during PI-FL period.

Table 3. Mean number of tillers per hill in the different treatments at different growth stages. Wet season 1993, Aduthurai, cvar ADT38.

DAT	Number of tillers per hill				
	T1	T2	T3	T4	L.S.D (0.05)
10	1.5	1.6	1.6	1.5	NS
23	3.1	4.6	4.0	4.0	NS
38	5.6	8.9	9.0	7.9	1.44
51	5.9	9.3	9.9	9.3	1.81
66	5.7	8.1	8.7	8.8	1.85
103	4.3	6.1	6.1	6.4	1.52

Table 4. Maximum number of tillers recorded in the different treatments at different crop growth stages (among observations from 4×20 hills in each treatment). Wet season 1993, Aduthurai, cvar ADT38.

Days after planting	Crop growth stage	Number of tillers per hill			
		T1	T2	T3	T4
0	Transplanting (TP)	1	1	1	1
10	Early tillering (ET)	3	4	3	3
23	Active tillering (AT)	9	11	14	9
38	Panicle initiation (PI)	15	19	27	20
51	Mid heading (MH)	16	21	30	24
66	Flowering (FL)	15	19	20	30
103	Harvest (HT)	14	18	15	27

Tiller loss started before flowering (Figure 2) in all the treatments and the loss was less in zero-N treatment than in others. During MH-FL period the tiller loss rate was higher in T2 and T3 from which it may be concluded that urea-N application at early stages tends to increase tiller loss during this period. The lower tiller loss rate during this period in T4, where urea-N was not applied upto 23 DAT, was the cause of the higher number of tillers at flowering.

When no N was applied, 25 % of total tillers were produced by 10 DAT (Table 5). In both T1 and T2, 95 % of the tillers were produced by PI while in T4 there were only 86 %

of total tillers. The ratio of productive to total number of tillers was lowest in T3.

As the grain filling in the crop suffered from a cyclonic storm and flooding, the grain yields were not significantly different among the treatments that received N, though they were higher than the control level.

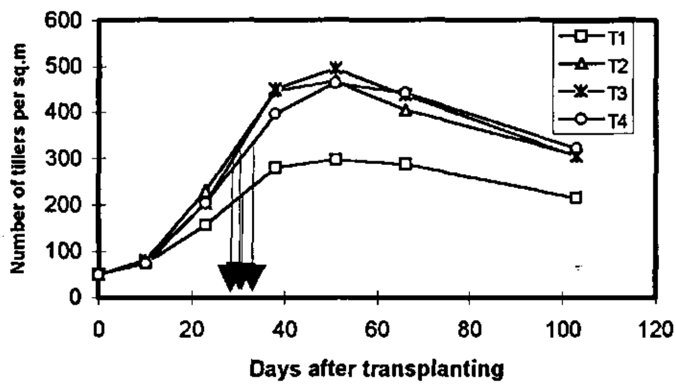

Figure 1. Time course of tiller density in the different treatments. The arrows indicate the time of last productive tiller. Wet season 1993, Aduthurai, cvar ADT38.

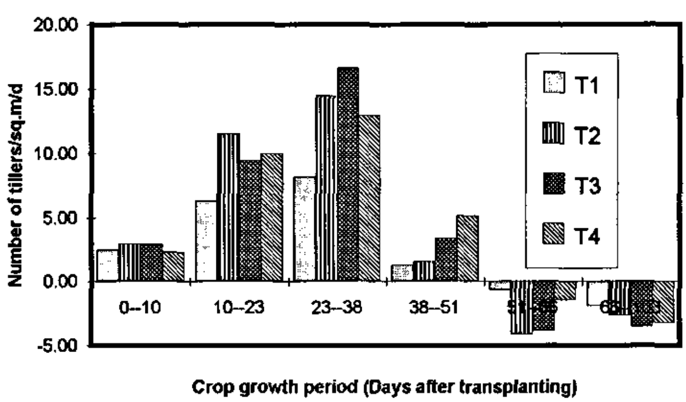

Figure 2. Tillering rate in the treatments during different crop growth periods. Wet season 1993, Aduthurai, cvar ADT38.

Table 5. Tillers in the different treatments at different stages of crop growth (percentage to maximum number of tillers per m^2). Wet season 1993, Aduthurai, cvar ADT38.

Growth Stage	T1	T2	T3	T4
Transplanting	16.7	10.6	10.0	10.8
Early tillering	25.0	18.1	16.0	16.1
Active tillering	53.3	50.0	41.0	44.1
Panicle initiation	95.0	95.7	86.0	86.0
Mid heading	100.0	100.0	100.0	100.0
Flowering	96.6	86.2	88.0	95.7
Harvest *	71.7	67.0	62.0	69.9

* productive tillers only

Conclusions

The tiller production rate was highest between 23 and 38 DAT and the maximum number of tillers per unit area occurred after PI (51 DAT) irrespective of N supply. The time of last productive tiller occurred around 30 days after transplanting. When urea-N was applied in combination with basally incorporated green manure, the tillering rate in the initial period (up to 23 DAT) was less than when urea-N was supplied alone. Tiller loss commenced between midheading and flowering and the loss was relatively less when urea-N application was delayed upto active tillering resulting in slightly higher number of productive tillers.

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Optimization of nitrogen distribution and of leaf area index for maximum canopy assimilation rate

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I. Optimum nitrogen allocation to leaves follows the light profile

Introduction

This part I of the paper deals with the question how a given quantity of nitrogen should be distributed over the leaf canopy to reach maximum canopy photosynthesis. Maximization of canopy assimilation may be viewed as a goal that is anthropocentric, irrelevant to plants. Yet, the evidence is that implementation of this goal leads to a nitrogen distribution similar to the one observed in the field. Many studies (see review in Van Keulen & Seligman, 1987) have shown strong positive correlations between photosynthetic capacity of leaves and their nitrogen content. In addition, these two characteristics are found to be correlated with the mean light exposure of leaves (Acock et al., 1978; DeJong & Doyle, 1985). Hirose & Werger (1987) investigated the optimum distribution of nitrogen over the leaf canopy, by optimizing its daily net CO_2 assimilation using a simulation method. Inserting measured relationships between nitrogen content and photosynthetic properties into a model for canopy photosynthesis, they found that most nitrogen should be allocated to the leaves that are located in the higher canopy levels, where they are exposed to higher radiation intensities.

The mathematical analysis presented in this paper shows that optimization of canopy photosynthesis leads to a distribution of nitrogen over the leaf canopy in such a way that photosynthetic capacity of leaves is proportional to the mean absorbed photosynthetically active radiation.

Description of leaf assimilation rate

At low irradiance gross CO_2 assimilation A (μg CO_2 m^{-2} s^{-1}) of leaves increases linearly with absorbed PAR H (W m^{-2}):

$$A = \varepsilon H \tag{1}$$

Eds. T.M. Thiyagarajan, H.F.M. ten Berge & M.C.S. Wopereis. Nitrogen management studies in irrigated rice. SARP Research Proceedings, AB-DLO, TPE-WAU, Wageningen and IRRI, Los Baños (1995), pp 85-97.

where ε is quantum efficiency in $\mu g\ CO_2\ J^{-1}$ (PAR).

For high irradiances the relationship between A and H levels off and approaches an asymptotic maximum A_m. The general expression for this type of relationship is:

$$A = A_m f(A_m, \varepsilon H) \tag{2}$$

where gross leaf assimilation is the product of maximum assimilation rate A_m (sometimes called photosynthetic capacity) and a dimensionless saturation function f which rises from 0 to 1 with increasing absorbed PAR. In almost all empirical expressions, A_m and εH occur together in the dimensionless combination $\varepsilon H/A_m$, for example:

$$A = A_m \min(1, \varepsilon H/A_m) \tag{3a}$$

$$A = A_m (1 - \exp(-\varepsilon H/A_m)) \tag{3b}$$

$$A = A_m (\varepsilon H/A_m) / (1 + \varepsilon H/A_m) \tag{3c}$$

$$A = A_m (1 + \varepsilon H/A_m - \{ (1 + \varepsilon H/A_m)^2 - 4\theta\varepsilon H/A_m \}^{0.5}) /(2\theta) \tag{3d}$$

which represents the Blackman response, the negative exponential, the hyperbola and the nonrectangular hyperbola, respectively. The latter function contains an additional parameter θ defining the shape of the function (Marshall & Biscoe, 1980).
These expressions for A can be generalised into:

$$A = A_m f(\varepsilon H/A_m, \text{and other parameters}) \tag{4}$$

The parameters A_m, ε and θ may vary simultaneously with nitrogen content N (g m^{-2}) of the leaf tissue. Note that f varies between 0 and 1.

Optimization of nitrogen distribution

Optimum distribution requires constant marginal returns of nitrogen with respect to leaf photosynthesis over the entire canopy. The rationale for this statement is simple: as long as the benefit of a small increase in nitrogen content is not the same for every leaf position in the canopy, the crop has not reached an optimum distribution yet, since improvement would still be possible by redistribution.

Translating this condition into mathematical terms implies that the derivative of A with respect to leaf nitrogen content N should be independent of leaf location. The effect of nitrogen content on dark respiration is neglected here, i.e. it is assumed that the optimization for net and gross assimilation rate is the same.
The first derivative of A with respect to N is given by:

$$dA/dN = d\,(A_m f\, \varepsilon H/A_m))/dN \tag{5}$$

For brevity of notation the 'other parameters' of Eq. 4 are omitted.

In this analysis it is assumed that nitrogen content only influences A_m. Optimization through other photosynthetic parameters such as ε, θ or dark respiration rate is not investigated since experimental evidence such as presented by DeJong & Doyle (1985) and by Hirose & Werger (1987) shows that they are much less dependent on nitrogen content.

The dependence of A_m on leaf nitrogen can be presented schematically by a linear relationship (Figure 1) where characteristics are used that are typical for C_3-species (Table 1).

Table 1. Parameter values used, typical for C_3-species. (Van Keulen & Seligman, 1987; Penning de Vries & Van Laar, 1982).

Threshold of nitrogen content for photosynthesis	N_b	0.3 g m^{-2}
Photosynthetic nitrogen use efficiency	α	1000 µg CO_2 m^{-2} s^{-1} $g(N)^{-1}$
Photosynthetic light use efficiency	ε	11 µg CO_2 J^{-1}
Extinction coefficient	K	0.7

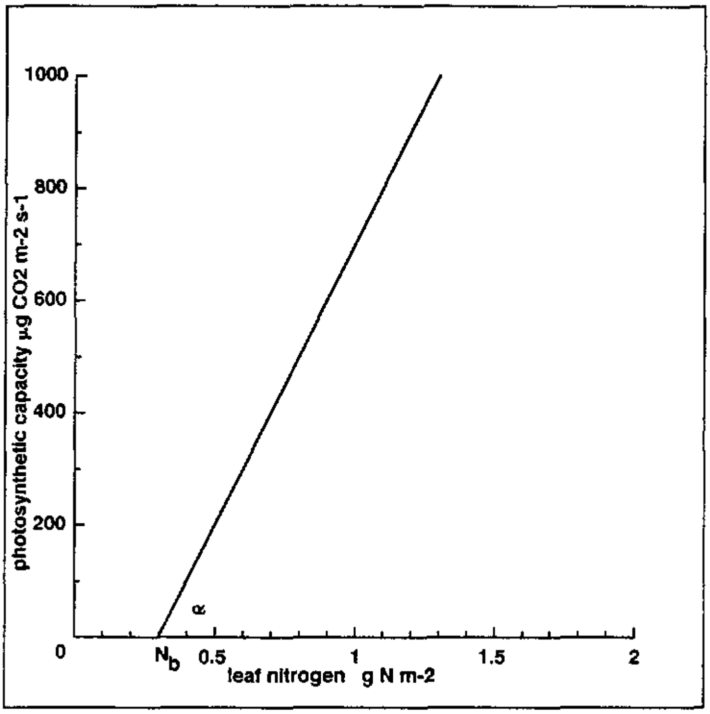

Figure 1. Maximum CO_2 assimilation rate per leaf area as a function of leaf nitrogen density. The typical level for the threshold N_b was 0.3 g m^{-2} and the slope α was about 1 mg of CO_2 s^{-1} g^{-1} of N.

The first derivative dA/dN can be written as:

$$dA/dN = f(\varepsilon H/A_m)\, dA_m/dN - A_m f(\varepsilon H/A_m) \varepsilon H/A_m 2 \; dAm/dN \tag{6}$$

or

$$dA/dN = \{f(\varepsilon H/A_m) - f(\varepsilon H/A_m)\, \varepsilon H/A_m\} \; dA_m/dN \tag{7}$$

Substituting ξ for the dimensionless group $\varepsilon H/A_m$ we find:

$$dA/dN = \{f(\xi) - \xi f(x)\} \; dA_m/dN \tag{8}$$

It is convenient to write the group $\{f(\xi) - \xi f(\xi)\}$, which is exclusively a function of ξ, as $g(\xi)$. Since A_m is assumed to be a linear function of N, the requirement that dA/dN must be the same for all leaves means that $g(\xi)$ must be identical for all leaves. This condition is always fulfilled if $g(\xi)$ is not really a function of ξ, but a constant. The problem can then be reduced to the differential equation $f(\xi) - \xi f(\xi) = c$, which can be solved and results in $A = \varepsilon H$. In this rather trivial situation A_m is so large that it has lost its effect on the actual assimilation rate. The other, more interesting situation is where the argument ξ is a constant. In other words, the dimensionless group $\varepsilon H/A_m$ should be the same for all leaves. Since ε was assumed to be constant, this requirement means that A_m should be proportional to absorbed radiation H. The conclusion is that the shape of the profile of A_m must be similar to the shape of the profile of H. As a first approximation, this shape is independent of light level, so that the shape of the optimum profile of A_m hardly varies during the day. If this optimum profile is reached, A_m can be expected to show an exponential decline with depth in the canopy, just as radiation does. The value of A_m at level L can be described by:

$$A_m = A_{m,0} \exp(-KL) \tag{9}$$

where K is the extinction coefficient for PAR, and $A_{m,0}$ the maximum leaf assimilation rate at the top of the canopy. L indicates canopy depth in terms over leaf area index above the considered level, and ranges between 0 and LAI.

According to Eq. 4, the assimilation rate of leaves can be written as

$$A = A_m f(\xi)$$

where ξ is now constant over canopy depth. Consequently, integration of A to find canopy assimilation rate is extremely simple and yields, using Eq. 9:

$$A_{tot} = f(\xi)\, A_{m,0}\, (1 - \exp(-K\, LAI))\, /K \tag{10}$$

The value of $f(x)$ can be calculated by substitution of the dimensionless ratio $\varepsilon KI_0/A_{m,0}$ into one of the response curves of Eq. 3. H at the top is equal to extinction coefficient K times incoming radiation I_0.

A conclusion that follows from the analysis given is that the "extinction" of A_m should be comparable to that of H. Indeed, Hirose and Werger (1987) found that the difference in nitrogen content between leaves in the top and in the bottom of the canopy increases with increasing LAI.

Benefit of optimization

The method presented so far is a qualitative one and does not derive the penalty for deviating from the optimum situation. Therefore a numerical model was used which compares canopy photosynthesis resulting from the optimized profile of A_m. with the one from a uniform profile of A_m. The conditions chosen were a low flux density of PAR (100 W m^{-2} incoming), and an A_m (uniform) at 100, 200, 400 and 1000 μg m^{-2} s^{-1} respectively. The optimized profile was constructed with the constraint of equal total A_m (i.e. equal total nitrogen) over the leaf canopy, so that the two profiles cross over. The photosynthesis-light response curve used was the negative exponential one. The results (Figure 2) indicate that any benefit of optimization begins to occur only above $LAI = 2$. For lower values of LAI the range of light intensities is too small for any appreciable benefit of translocating nitrogen from below to above. For the highest value of A_m chosen (1000 μg m^{-2} s^{-1}) the benefit is less again than for lower values. For this high value of A_m even the top leaves are far from light saturation, and translocation from below to above helps little. The conclusion is that optimization is only of appreciable benefit for high values of LAI, in combination with noticeable light saturation in the top of the canopy.

Discussion

In hedgerow type canopies the radiation profile is not exponential, and the distribution of radiation tends to vary strongly with the position of the sun. Still, in such conditions the nitrogen distribution is expected to correspond to the distribution of mean irradiation. DeJong & Doyle's (1985) observation that A_m is well correlated with the number of hours that H exceeds some arbitrary threshold level is in agreement with this line of thought.

The derivation in the analysis presented here does not depend on the precise shape of the photosynthesis-light response curve. Whether it is described by a rectangular hyperbola or some other equation of the type of Eq. 4, the main conclusion is the same. However, if other photosynthetic parameters such as θ and ε are also a function of the nitrogen content, the analysis will be much more complicated, and the conclusion may be slightly modified. This analysis did not include respiratory costs of the redistribution process itself.

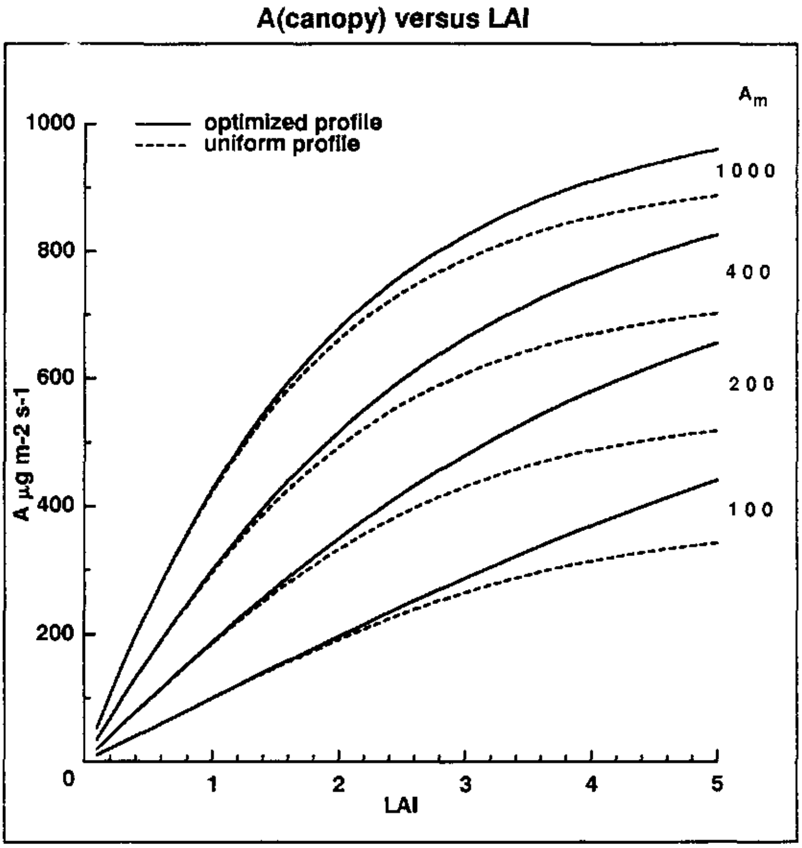

Figure 2. CO_2 assimilation rate of the leaf canopy for an optimized and for a uniform profile of A_m. The photosynthesis-light response curve was the negative exponential one. Parameter values were as those given in Table 1. A_m (uniform) was chosen at 100, 200, 400 and 1000 µg of CO_2 m^{-2} s^{-1} respectively, and A_m (optimized) calculated so that the same levels of total A_m integrated over the leaf canopy was obtained.

These costs will cause a delay in the realization of the real optimum profile and make it more uniform than the theoretical one derived here, especially in a fast growing crop (Field, 1983). Also, the response of photosynthesis to nitrogen may level off at higher nitrogen concentrations, so that the benefit of high nitrogen concentrations in top leaves may be reduced.

There is no question that in leaf canopies the expected relation of leaf nitrogen content with mean irradiation does exist. The mechanism to achieve such a correlation may be based on feedback as well as on feedforward processes. If governed by feedback processes, the leaves that are more illuminated are stronger sinks for nitrogen than the more shaded leaves, which may then even export their nitrogen. A simple feedforward process on the other hand is just an ontogenetic decrease of nitrogen content with leaf age. Older leaves automatically tend to be more shaded, so that the optimum distribution is automatically approached (Field, 1983). However, in free standing plants the radiation-nitrogen correlation should then no longer exist.

II. Optimum *LAI* as a function of incoming radiation and total available nitrogen

Introduction

As shown in Part I, nitrogen distribution over the leaf canopy can be optimized if the distribution of leaf nitrogen concentration is the same as that for PAR extinction. For high values of *LAI* (> 2) considerable increases in canopy assimilation rate can be reached. Further optimization for a given quantity of leaf nitrogen N, available per unit ground area is possible by changing the value of *LAI* itself as well.

If in an extremely nitrogen-poor situation all leaves are depleted to the minimum level N_b, their rate of assimilation will drop to zero. Then at least some canopy photosynthesis could be achieved, just by reducing *LAI* in order to increase the nitrogen content of the remaining leaves above the threshold level N_b. Somewhere in the range between $LAI = 0$ and $LAI = N_{tot}/N_b$, an optimum value of *LAI* exists where increase of photosynthetic performance just compensates for reduced light interception. The dependence of canopy photosynthesis on *LAI*, given total leaf nitrogen N_{tot}, is the subject of this part of the paper.

The nitrogen profile

Since A_m (Figure 1, Part 1) is given by a (N - N_b), the nitrogen profile in the optimized situation follows as

$$N = N_b + A_{m,0} \exp(- K L) / \alpha \qquad (11)$$

The total amount of leaf nitrogen per unit ground area is the integral of N over leaf area, and can be found analytically from integrating Eq. 11 to yield:

$$N_{tot} = N_b\, LAI + A_{m,0}\, (1 - \exp(- K\, LAI))/ (K\alpha) \qquad (12)$$

Since N_{tot} will be considered as a constant, it is more convenient to express $A_{m,0}$ as a function of N_{tot}:

$$A_{m,0} = K\, \alpha\, (N_{tot} - N_b\, LAI) / (1 - \exp(- K\, LAI)) \qquad (13)$$

Canopy photosynthesis

The particular shape of the optimized profile of A_m provides the possibility of a simple analytical integration of A over the leaf canopy (Eq. 10, Part 1).

Combination with Eq. 13 gives:

$$A_{tot} = f(\xi)\, \alpha\, (N_{tot} - N_b\, LAI) \tag{14}$$

The function $f(\xi)$ indicates the degree of light saturation of individual leaves (Eq. 3), and has a value between 0 and 1. In the assumed situation of optimized nitrogen distribution it is the same for all leaves, because light and A_m decrease similarly with canopy depth. Then $f(\xi)$ can just as well be calculated from the value of ξ at the top of the canopy:

$$\xi = \varepsilon\, KI_0 / A_{m,0} \tag{15}$$

substituted into one of the saturation type curves of Eq. 3.
Using Eq. 13 this expression can also be written as

$$\xi = \varepsilon\, I_0\, (1 - \exp(-K\, LAI)\ )\, /\, (\alpha\, (N_{tot} - N_b\, LAI\,) \tag{16}$$

For low values of ξ the function $f(\xi)$ approaches ξ itself. Substitution into Eq. 14 gives

$$A_{tot} = \varepsilon\, I_0\, (1 - \exp(-K\, LAI)\ ) \qquad \text{for low } \xi \tag{17}$$

This curved relation describes the light limitation of canopy photosynthesis, which is the case for low values of LAI in combination with a high amount of leaf nitrogen, or for low values of radiation. For high values of ξ on the other hand, the value of $f(\xi)$ will tend to unity. A_{tot} is then given by

$$A_{tot} = \alpha\, (N_{tot} - N_b\, LAI) \qquad \text{for high } \xi \tag{18}$$

This is a linear relationship with LAI, but with a negative slope. It describes the region with nitrogen limitation, which occurs for high values of LAI, in combination with a relatively low amount of leaf nitrogen, or for high radiation levels. Canopy assimilation follows these limits rather precisely if leaf assimilation follows the Blackman type of response curve (Figure 3). Then in the optimized profile all leaves switch simultaneously from light limitation to nitrogen limitation when the optimum value of LAI is passed. The location of the optimum is then identical to the location of the intersect of the two upper boundaries, and can be calculated by combining Eq. 17 and 18. Unfortunately, this results in an implicit expression for LAI. However, for low LAI a reasonable indication of the location of the optimum can be found by combining Eq. 18 with the low LAI version of Eq. 17,

$A_{tot} = \varepsilon\, I_0 K\, LAI$, which gives:

$$LAI_{opt} = \alpha N_{tot} / (\varepsilon I_0 K + \alpha N_b) \qquad LAI < 1 \qquad (19)$$

If the result of Eq. 19 yields a value of LAI larger than 5, it is better to assume full soil cover and Eq. 17 should be simplified to $A_{tot} = \varepsilon I_0$. Combination with Eq. 18 then gives:

$$LAI_{opt} = (\alpha N_{tot} - \varepsilon I_0) / (\alpha N_b) \qquad LAI > 5 \qquad (20)$$

Both equations show clearly that the optimum value of LAI gets larger for increasing total nitrogen N_{tot}, for decreasing nitrogen threshold N_b, and for decreasing radiation I_0. Because of the implicit occurrence of LAI, Eq. 19 and 20 are only valid for the extreme ranges of LAI. For N_{tot} however, the combination of Eqs. 17 and 18 returns an explicit solution, which must be interpreted as the level of N_{tot} where nitrogen limitation switches to light limitation:

$$N_{tot,switch} = N_b\, LAI + \varepsilon\, I_0\, (1 - \exp(-K\, LAI))\, / \alpha \qquad (21)$$

When a value of 5 is substituted for LAI into this equation, nitrogen limitation will have disappeared entirely for values of N_{tot} larger than 5.8 g of N m^{-2}, using the parameter values as given in Table 1, and a radiation level I_0 of 400 W(PAR) m^{-2}. If LAI is only 2, the nitrogen requirement is much less, at 3.9 g N m^{-2}.

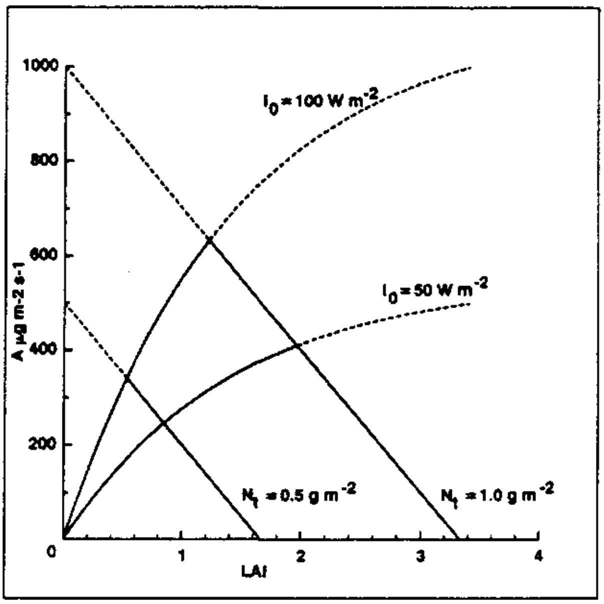

Figure 3. Nitrogen and light limitations to canopy assimilation rate for an optimized nitrogen distribution. Photosynthesis-light response curve was the Blackman response, with parameter values as given in Table 1.

Benefit of an optimized nitrogen profile

The expressions for A_{tot} given above were derived for the optimized profile, which enables simple analytical expressions. In other situations, of which the uniform profile is the simplest one, numerical procedures must replace these expressions. An example of such a numerical evaluation for the dependence of A_{tot} on *LAI* is shown in Figure 4. In the nitrogen-poor situation the difference between the optimized and the uniform profile is very small. This result is in accordance with part 1, where it was shown that optimization of the profile has hardly an effect below an *LAI* of about 2. When there is more nitrogen available, the optimum *LAI* shifts upward, both in the optimized and in the uniform profile, but more so in the optimized profile. In other words, non-optimized nitrogen profiles mean a lower value of optimum *LAI*, and stronger expression of nitrogen limitation.

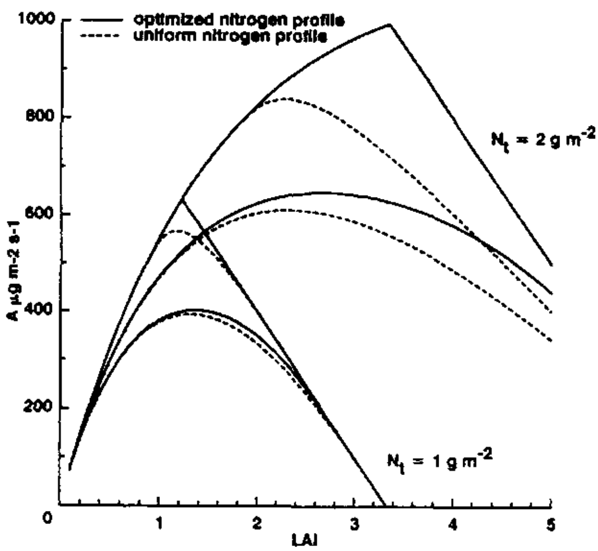

Figure 4. Canopy photosynthesis as a function of *LAI* with a fixed amount of total leaf nitrogen N_{tot} of 1 and 2 g m^{-2} (ground area) respectively. The strongly peaked curves result from the Blackman light-response curve of leaf photosynthesis, the more gradual ones from the negative exponential one. Optimized and uniform nitrogen profile had the same amount of total leaf nitrogen and I_0 was 100 W m^{-2}. Other parameters were as in Figure 1 and in Figure 3.

From instantaneous rates to daily total of assimilation

For reasons of simplicity the diurnal course of irradiation was supposed to be sinusoidal over a 12 hour day. This diurnal course was imposed on the model that is formed by the equations given above, and the instantaneous assimilation rate was integrated to give the diurnal total. The results for the Blackman type response and also for the negative exponential curve are presented in Figures 5a and 5b. The sharp transitions in the Blackman response have been smoothed through the variation of radiation during the day, but the peaks are still more pronounced than for the negative exponential response curve. In both graphs the optimum *LAI* clearly decreases with increasing radiation level.

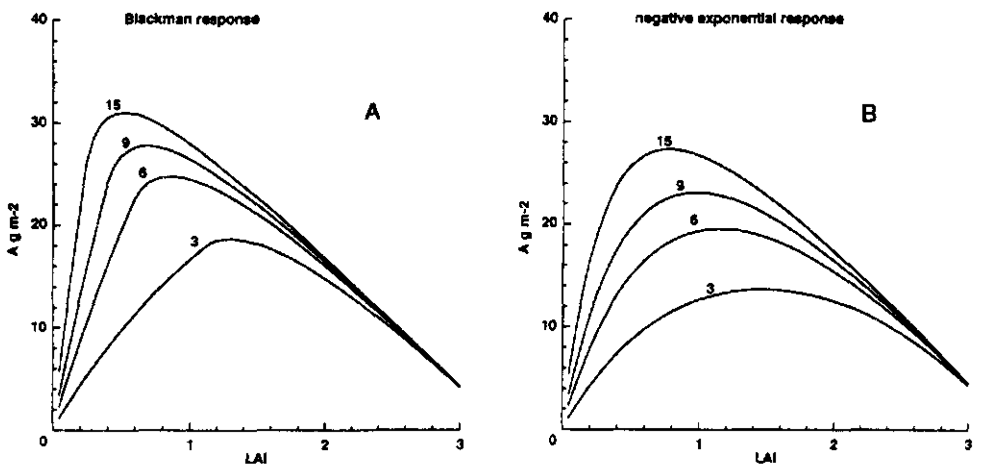

Figure 5. Daily totals of canopy assimilation for four levels of daily total of PAR (3, 6, 9 and 15 MJ m^{-2}). The nitrogen distribution was supposedly optimal. In Figure 5a the curves are shown for the Blackman response and in Figure 5b for the negative exponential relationship.

Discussion

When the light level increases, the light-limited assimilation is also increased, so that the optimum value of *LAI* is decreased (Figure 3). This effect is not important when the available nitrogen is high, since the optimum *LAI* is then determined by respiratory costs (not considered here) rather than by nitrogen limitation. However, in nitrogen-poor situations high radiation levels will induce a low value of *LAI*, which in practice is hard to distinguish from an effect of water shortage.

The precise shape of the optimum curve of A_{tot} versus *LAI* depends on the photosynthesis-light relationship chosen. The effect of the type of response curve is shown in Figure 6, where the relationship of A vs. *LAI* is given for five irradiation fluxes and for the Blackman and negative exponential relationship respectively. In case of a Blackman response there are clear-cut boundaries as shown in Figure 3, but for the negative exponential the calculated values of A_{tot} are always lower.

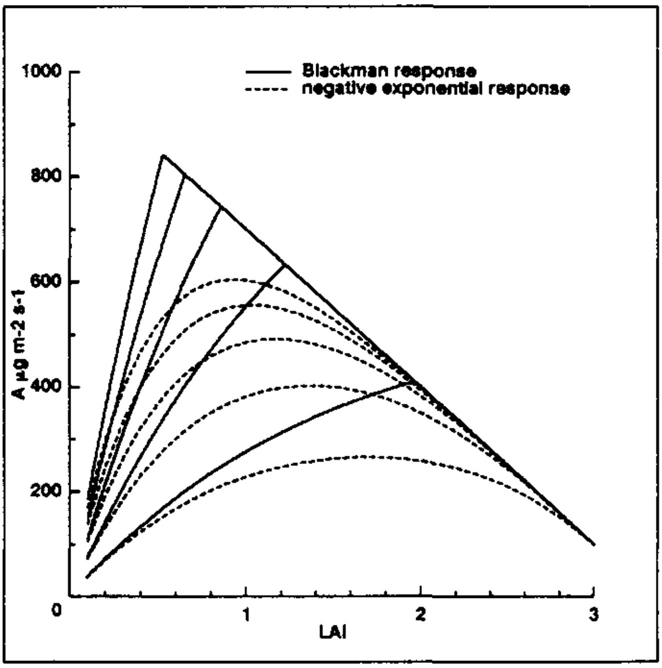

Figure 6. Canopy assimilation rates for five levels of irradiation (50, 100, 150, 200 and 250 J of PAR m^{-2} s^{-1}). The other parameters were the same as in Figure 3. The relationships shown were as calculated for a Blackman type response and for a negative exponential relationship. The nitrogen distribution was always supposedly optimal.

The remarkable decrease of optimum *LAI* with increasing irradiation is maintained for the negative exponential photosynthesis-light response curve, although the effect is less pronounced than for the Blackman response.

Summary

Maximum canopy assimilation rate is reached when the nitrogen distribution over the leaf canopy follows the light profile. This conclusion is derived by a mathematical analysis, using experimental evidence for a linear relation between leaf photosynthetic capacity and its nitrogen content. No assumptions on shape of profile are needed to arrive at this conclusion. The effect of this optimization for canopy photosynthesis becomes only noticeable above a value of *LAI* of 2.

For a given amount of total leaf nitrogen there is an optimum value of *LAI*, determined by light interception on one hand and total leaf nitrogen on the other. Because there is a minimum nitrogen requirement in leaves for photosynthesis, canopy assimilation decreases with increasing *LAI* above this optimum level of *LAI*. This optimum rises with decreasing radiation, increasing total leaf nitrogen, and decreasing minimum nitrogen content in leaves.

Acknowledgement

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Procedure for collecting plant samples at different growth stages of transplanted rice crop

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Proper sampling of plant material is as important as preparation and analysis for reliable interpretation of results. Especially when plant sampling at different growth stages is required, the number of samples may become large in experiments with various replicated treatments. Then it becomes important that representative samples are collected in order to contain the total number of samples within acceptable limits.

According to Gomez & Gomez (1984), an appropriate sample is one that provides an estimate or a sample value, that is as close as possible to the value that would have been obtained had all plants in the plot been measured and a good sampling technique is one that gives small sampling error. The caution to be exercised in plant sampling has been emphasized by Jones & Case (1990) by indicating that there is substantially large potential for errors to occur due to improper sampling technique and if the sample taken is not representative of the general population, all the careful and costly work put into subsequent analysis will be wasted. Obtaining a representative sample is a complex task, and some expert knowledge is required in addressing it. They suggested that samples of 50-100 rice plants will usually be sufficient. Gomez & Gomez (1984) prescribed that sample size be based on the variability and by the degree of precision required for the character of interest. The sampling designs described by those authors are often impractical in experiments with frequent samplings.

We propose here a sampling strategy that is based on prior information on 'what is a representative plant'. This information is a set of observations of tiller numbers per hill and can thus be collected 'non-destructively'. Once we can be sure to collect representative plants, the total sample size may remain small. The number of tillers per hill may vary quite considerably (Table 1). The sampling procedure is explained below.

Plot size

The required plot size depends on the total number of hills to be collected as samples may have to be collected throughout the duration of the experiment. We usually adopt a plot size of 40 m^2 for each treatment in each replication, as sufficiently large for our crop dynamics studies. This plot will be a single unit for all management and treatment

Table 1. With-in plot heterogeneity in the number of tillers per hill as observed in some nitrogen management experiments.

Hill number	Number of tillers per hill		
	Aduthurai 1992, WS cv. ADT38	Thanjavur 1992, DS cv. IR64	Aduthurai 1993, WS cv. ADT38
1	4	3	18
2	6	5	10
3	10	9	3
4	5	10	7
5	8	8	7
6	11	11	17
7	3	10	10
8	9	7	6
9	10	10	12
10	5	4	2
11	7	5	6
12	6	7	4
13	4	9	10
14	8	10	8
15	6	10	20
16	7	12	12
17	13	13	8
18	6	7	7
19	8	8	10
20	6	6	10
Mean	7.1	8.2	9.4
S.D.	2.6	2.7	4.7
C.V.(%)	35.9	32.8	50.0

purposes. For plant sampling, half of the plot i.e. 20 m^2 (uniformly on one side of all plots) is demarked and the other half is allowed undisturbed for final harvest.

Sample size
5 hills per plot

Sampling technique

Two border rows at the periphery of the sampling area are avoided for sampling. A hill in any other row is first located randomly. From that hill nine other consecutive hills in the same row, away from the nearest border, are observed. Tiller numbers and noted down serially (1-10). In the same sampling area on the diagonally opposite side (Figure 1) tiller observations are done in 10 other hills (11-20). Then, the mean tiller number for the 20 hills is calculated. If the mean tiller number is 7.2, for example 5 hills with tiller numbers 6, 6, 7, 8 and 8 (i.e. one hill with mean tiller number, 2 hills with (mean-1) tiller number and 2 hills with (mean+1) tiller numbers are to be sampled. The 5 hills with required number of hills may be found among 20 hills already counted or from the neighbouring area. The 5 selected hills are be carefully pulled out, preferably along with the roots.

Obviously, hill selected for sampling shall be surrounded by properly spaced hills on all four sides.

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Figure 1. Selection of hill for tiller counting. The hills used for counting are marked 'X'.

Processing of samples

After collection, the plant samples must be a) cleaned to remove surface contamination, b) (if required) separated into roots, stem (leaf sheath plus culm), leaves (leaf blades) and panicles, c) oven dried (80°C) to stop enzymatic reactions and remove moisture and weights recorded and d) each sample is ground to homogenous fine material; sub samples are obtained for laboratory analysis. If drying is carried out in ovens, it is possible that samples in the core of the oven do not dry properly. This may result in gross overestimation of produced biomass, apart from the problems of sample conservation To avoid this, the samples in paper covers can be sun dried (with turning over) first, before loading in to the oven, taking care to avoid any contamination. In the oven, samples should be well spaced to allow sufficient air flow.

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Soil Fertility Evaluation

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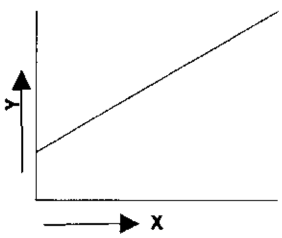
With the introduction of high yielding varieties and improved production techniques there has been a phenomenal increase in the production of cereals world-wide, particularly in South East Asia, in the last three decades. The new varieties have helped to substantially improve the yield potentials of crops, but, these potentials can be reached only with adequate supply of inputs. Of the inputs, it has been estimated that fertilizers have contributed to a little over 40% of the increase in productivity (Tandon, 1993). Fertilizer application can be economic and would bring about the expected yield increases only if used judiciously, taking into account the crop requirement and soil status. Soil fertility evaluation aims to find out how much nutrient the soil can supply and how much more has to be added to the soil by external application to achieve the desired yield level.

Traditionally farmers have been applying manures to their crops based on their experience and by trial and error. Systematic efforts to assess the soil fertility status and crop responses to nutrient application started in the late 1800's in Europe.

Law of minimum

The law of minimum was one of the first attempts to explain the nature of soil fertility. Though De Saussure, a Swiss chemist and Springel, a German agricultural chemist, are reported to have formulated the law, elaboration and verification of the law were attributed to Liebig. Liebig stated the law as follows: 'The crops on a field diminish or increase in exact preparation to the diminution or increase of mineral substances conveyed to it in manure, and by the deficiency or absence of one necessary constituent, all others being present, the soil is rendered barren for all these crops to the life of which that one constituent is indispensable' (Russel, 1961). This, in other words, means that the relationship between the quantity of nutrient (x) and yield (y) is linear as long as x is the limiting factor and all other factors are in ample supply. This can be graphically represented as follows:



As per this law, the yield response would proportionately increase to the increment in nutrient supply. A large number of experiments has been carried out to verify this law and the results show that the law holds at low levels of application, so that the nutrient that is being tested is actually the limiting factor. Once this deficiency is alleviated by application of the nutrient, the response to that nutrient is no longer linear as other factors (e.g. other nutrients) become limiting. Under field conditions, where more than one nutrient may be in short supply, it has been found that linear relationship does not hold. Hence Liebig's law of minimum is not widely used in soil fertility studies.

Law of Diminishing Yield Increment

Mitscherlich (1909) propounded this law based on the results of a large number of field experiments in Germany. When a nutrient is added to the soil, initially there is a rapid increase in yield but as the input level increases, the yield increment obtained for every input increment becomes smaller and smaller. The curve approaches a plateau. This can be mathematically expressed as,

$$dy/dx = (A-y)\, c$$

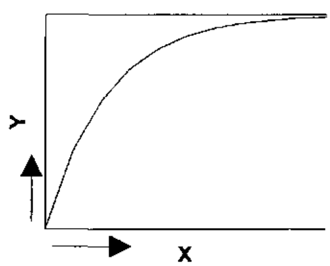
where dy/dx is the yield increment obtained per increment dx of the nutrient. A is the maximum yield attainable when the growth factor is present in optimum quantity and c is a proportionality constant. By integrating the above equation and converting to logarithm to the base 10, it becomes

$$\log (A-y) = \log A - cx$$

It can also be expressed in the exponential form as

$$y = A\,(1-10^{-cx})$$

The equation can be graphically represented as follows:



The above equation expresses the following : There is a maximum yield A of the crop for a given set of agroecological conditions; the yield increment from resulting from nutrient addition is proportional to the difference between the maximum yield and the actual yield Y.

Since it was not always possible to quantitatively define the absolute yield values, Baule, a German mathematician, proposed that the yield responses could be expressed as percentages of the maximum yield. He suggested an 'effect quantity' which was inversely proportional to Mitscherlich's *c* value. This came to be known as Baule unit. One Baule unit will increase yield by 50% of the difference between maximum and actual yield; two Baule units by 75% and so on. Baule also suggested that in a situation where multiple nutrients are involved, Mitscherlich equation becomes,

$$y = A\,(1\text{-}10^{-c_1 x_1})\,(1\text{-}10^{-c_2 x_2})\,......\,(1\text{-}10^{-c_n x_n})$$

where c_1, c_2.....c_n are proportionality constants for nutrients x_1, x_2......x_n, respectively. Using percentages instead of absolute values is useful in comparing situations of different nature or responses to different nutrients. Baule's modification of Mitscherlich law is called the percentage sufficiency concept. Three points emerge from this concept : (1) maximum yield referred in the concept is the maximum only for the test conditions, all growth factors being constant but not necessarily at their optimum; (2) maximum yield can always be approached but never reached mathematically and (3) if other controllable growth factors are below their optimum, higher yields can be produced in proportion to the levels of these factors (Bear, 1965). The third point is of considerable significance. The final yield obtained is the product of the individual percentage sufficiency's and not the one decided by the minimum factor percent, which is in contrast to Liebig's law. For example, in a given situation, nitrogen present is sufficient to produce 90% of the maximum yield ; phosphorus to produce 80 per cent, and potassium to produce 70 per cent. According to Liebig's law, potassium is the most limiting nutrient in this case and the yield that could be obtained is only 70% of the maximum. But, as per the percentage sufficiency concept, the final yield is the product of 90 x 80/100 x 70/100 = i.e. 50.4% of the maximum yield.

Bray (1954) evaluated Mitscherlich law extensively and found some limitations in the use of the law. Mitscherlich's assertion of constancy of *c* for a given nutrient did not always hold well and the *c* value was modified by such factors as type of plant, planting pattern and rate, form of nutrient and its distribution in the soil. Hence c has to be derived for a given set of agroecological conditions for each crop and nutrient. Bray also suggested that Liebig's law could be applied to nutrients that are easily soluble and mobile in the soil (e.g. NO_3-N) and Mitscherlich's law to relatively immobile nutrients like H_2PO_4, K^+, NH_4^+ and micro nutrients. Bray found that no distinction was made between soil nutrient and applied nutrient in the Mitscherlich equation. Hence he modified the equation as,

$$y = A(1\text{-}10^{-cx-c_1 b})$$

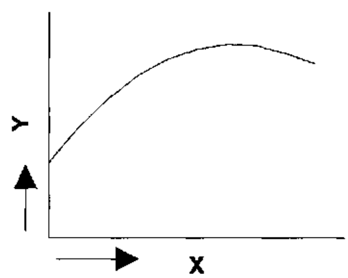
where c_1 refers to the efficiency of soil or native nutrient and b to the quantity of soil nutrient available to the crop, as estimated by soil test. This modified equation is referred to as Mitscherlich-Bray equation and is extensively used in soil testing services in many parts of the world. The major lacuna in using the Mitscherlich-Bray equation is that it does not stand direct statistical scrutiny.

Statistical approach

Many experiments were planned in the 1960 's and 1970 's to find the full form of response curves over large rates of fertilizer applications (Cooke, 1972). FAO Manual (1966) states that a quadratic equation works quite satisfactorily over a wide range of levels of application and can be statistically scrutinized. It takes the form,

$$y = a + bx - cx^2$$

where y is the yield obtained when x units of nutrient are added and a, b and c are constants. The values of a, b and c can be calculated statistically by least square method. The equation can be graphically expressed as follows.



The economically optimal level of nutrient application can be calculated by equating the first order derivative of the equation to the price ratio of the input to the output.

$$dy/dx = b\text{-}2cx = P_y/P_x$$

where P_y *is the price per unit quantity produce and* P_x *is the price of unit quantity of* nutrient applied. (Of course, this can also be done for the Mitcherlich equation). The Quadratic model is extensively used to quantify agronomic data on yield responses to fertilizer application.

Regression models

Blanket recommendations of fertilizer application to crops are still widely made, after grouping the soils into high, medium and low levels of nutrients using statistical techniques. The recommended dose is then defined for medium category soils. This should be increased by 50% for low category soils and reduced by 50% for high category soils. This type of blanket recommendation does not take into account the variations due to agroecological conditions and management factors.

With the introduction of high yielding varieties and crop intensification, location specific fertilizer recommendations based on soil supplying capacity and crop requirement are needed to produce high yields, increase the economic returns and maintain soil health. This becomes all the more imperative with the escalating cost of fertilizers.

Ramamoorthy & Velyutham (1971) expounded a methodology for making soil test based fertilizer recommendation to achieve a targeted yield. A large plot (about 0.5 ha) is selected in a homogenous area in a representative soil family site. The plot is divided into four strips, one receiving no fertilizer, one half the level, one full level and the last, one and half the level of N, P and K. The level is determined by the level of N at which the maximum response is obtained for N. For P and K, the level is equal to their fixing capacities in the soil. Twenty one or twenty four treatment combinations with five levels of N, four levels of P and three levels of K, in addition to 4 to 6 controls, are randomly allotted in each of the four strips. An exhaust crop is first grown to bring uniformity before treatments are imposed. Then the test crop is raised. Soil samples are collected from each plot and analysed for soil nutrient status using the standard soil test method. After harvest of the crop, plant samples are analysed for their nutrient content and uptake calculated. Using these data, a multiple regression equation is set up using regression analysis. The equation takes the following form :

$$y = a + b_1\,SN - b_2\,SN^2 + b_3\,SP - b_4\,SP^2 + b_5\,SK - b_6\,SK^2 + b_7\,FN - b_8\,FN^2 + b_9\,FP - b_{10}\,FP^2 + b_{11}\,FK - b_{12}\,FK^2 + b_{13}\,SN\,FN + b_{14}\,SP\,FP + b_{15}\,SK\,FK$$

where a refers to (y - intercept) , b's to regression coefficients, S and F to soil and fertlizer nutrients and y to crop yield. The response category, (+) for the first order coefficient (-) for the second order coefficient and (-) for the interaction coefficient, is appropriate and works well. Using this equation fertilizer prescriptions are made using the following formulae (example for N):

$$FN = B7/2B8 - B13/2B8 \bullet SN \qquad \text{(for maximum yield)}$$
$$FN = B7/2B8 - B13/2B8 - 1/2B8 \bullet R \qquad \text{(for economic yield)}$$

The three parameters required for making fertilizer recommendations are calculated as follows.

1. kg nutrient required (per q (100 kg) grain production) $= \dfrac{\text{total nutrient uptake at harvest } \left(\text{kg ha}^{-1}\right)}{\text{grain yield } \left(\text{q ha}^{-1}\right)}$

2. % contribution of nutrient from soil $= \dfrac{\text{nutrient uptake in control plot } \left(\text{kg ha}^{-1}\right)}{\text{soil test value for the nutrient in the control plot } \left(\text{kg ha}^{-1}\right)}$

3. % contribution of nutrient from the fertilizer =

$$\frac{\left(\text{nutrient uptake } \left(\text{kg ha}^{-1}\right)\right) - \left(\left(\text{soil test value } \left(\text{kg ha}^{-1}\right)\right) \times (\%\text{ contribution from soil})\right)}{\text{fertilizer nutrient applied } \left(\text{kg ha}^{-1}\right)}$$

From these parameters the fertilizer recommendation for a targeted yield can be calculated as follows:

$$FN = AT - B\,SN$$

where

T = yield target in q ha^{-1},
A = NR/CF
B = CS/CF
NR = nutrient requirement in kg/q of produce
CF = per cent contribution from the fertilizer nutrient
CS = per cent contribution from soil available nutrient and fertilizer nutrient.
FN = fertilizer nutrient (kg ha^{-1})
SN = soil nutrient (kg ha^{-1})
q = quintal (100 kg)

This inductive approach of Ramamoorthy has been extensively used in the Soil Test - Crop Response studies in India. Once a multiple regression model is developed for a crop for a given soil series/family, targeted yield fertilizer prescription equations are derived and used for making fertlizer recommendations. Before going for adoption by farmers, the validity of the equations is test verified in farmers' fields in similar soil series/families, in addition to working out the benefit-cost ratio for the recommendations. Based on the results, extrapolations are done in similar soil series/families.

Basic requirements for sound fertilizer recommendations

In a given agroecological and management situation, the production potential of the crop/genotype should be known. This can be collected from multilocation or adaptive research trials conducted by the plant breeders or agronomic trials conducted in the location. Based on the yield potential, an economic yield target can be set. Nutrient requirement for achieving the targeted yield should then be carefully assessed. This information can be obtained from nutrient response studies. Of the total nutrient requirement, it should be estimated as precisely as possible how much the soil can supply. A suitable soil testing method will give the soil supplying capacity. In soil test-crop response studies, the available soil test methods should be evaluated by correlating with response data and the most suitable method should be selected based on its high correlation with crop response and the easy adaptability of the method in soil testing laboratories. Once the soil supply is assessed, the rest of the crop requirement has to be met by external supply of nutrients through manures and fertilizers. The quantity of fertilizer and/or manure to be applied can be derived by using any one of the approaches/concepts suited to the situation. With the availability of computers this task has become easier, since a large number of models can be tested for their goodness of fit to the basic response data generated and the fertilizer recommendations. Ultimately, economics of fertilizer application has to be given careful consideration as the doses recommended are bound to vary, depending on current prices of fertilizers and crop outputs.

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